MSS Radiometric Calibration Finalization

Landsat Science Team Meeting

Mountain View, CA

January 19, 2010

Dennis Helder

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Image Processing Lab

Outline

- Objectives
- Methodology Updates
- Cross-calibration of MSS Sensors
- Lmin – Lmax Finalization

- Acknowledgements:
  - Landsat Project Science Office—Brian Markham, Julia Barsi
  - USGS EROS—Esad Micijevic, Obaidul Haque
  - SDSU IP Lab—Josh Mann, Sadhana Karki

Objectives

- Develop final MSS cross-calibration within radiance space.
- Describe updated methods
- Describe final rescaling (Lmin & Lmax)
- Describe remaining uncertainties

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Recent Cross-calibration Improvements

- The previous cross-calibrations of Landsats 2 to 4 and Landsats 4 to 5 were based on the acquisition of a single day's scenes. This method does not necessarily give a true representation of the cross-calibration gains and biases.
  - The new cross-calibration gains and biases are calculated using the whole life-time response of the sensor.
- New Improved Sensor-to-Sensor Calibration Path:
  - Previous: Landsat 1→Landsat 2 → Landsat 4 → Landsat 5, Landsat 3 → Landsat 4 → Landsat 5
  - **Updated**: Landsat 1 → Landsat 2 → Landsat 3 → Landsat 4 → Landsat 5

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Recent Cross-calibration Improvements

- Previously, to form the cross-calibration equations, only two formats of MSS (MSS-A and MSS-X) were used. However, in the recent cross-calibration equations, all three formats (i.e. MSS-P) are used to develop the equations.
- Additional regions of interest (ROIs) were added to obtain a better linear fit to a broader dynamic range.
- Radiance-based approach eliminated the need for solar models.
- Eliminate unneeded bias factors

Methodology Update: Normalized Radiance

TOA Reflectance Value

Previous:
(Reflectance based approach)

$$\rho_{TOA} = \frac{\pi \times L_\lambda \times d^2}{Esun_\lambda \times Cos\theta}$$

Updated:
(Radiance based approach)

$$L'_\lambda = \frac{\rho_{TOA} \times Esun_\lambda}{\pi} = \frac{L_\lambda \times d^2}{Cos\theta}$$

where,

ρ_{TOA} = TOA reflectance
L_λ = Spectral radiance value *(units: W/m² sr μm)*
L'_λ = TOA radiance normalization value *(units: W/m² sr μm)*
d = Earth-Sun distance in astronomical units *(AU)*
$ESUN_\lambda$ = Mean solar exoatmospheric spectral irradiances *(W/m² μm)*
θ = solar zenith angle *(units: degrees)*

Methodology

The equation of TOA radiance normalization is

$$L'_{\lambda(Ln)} = \mathrm{L}_{\lambda(Ln)} \times \frac{\mathrm{d}^2}{\mathrm{Cos}\,\theta}$$

where,

$L'_{\lambda(Ln)}$ = normalized radiance of Landsat 'n' MSS *(units: W/m² sr µm)*

$L_{\lambda(Ln)}$ = original radiance value of Landsat 'n' MSS *(units: W/m² sr µm)*

d = Earth-Sun distance in astronomical units *(AU)*

θ = solar zenith angle for the image portion of interest *(units: degrees)*

Updated: **Cross Calibration Procedure:**

1. Landsat-1 to Landsat-2
2. Landsat-2 to Landsat-3
3. Landsat-3 to Landsat-4
4. Landsat-4 to Landsat-5

Cross-calibration of Landsat 1 to 2 MSS

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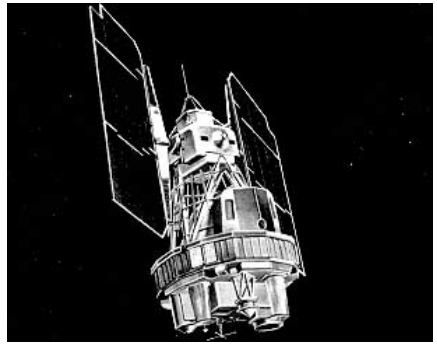


Site used for Cross-calibration of Landsat 1 to 2

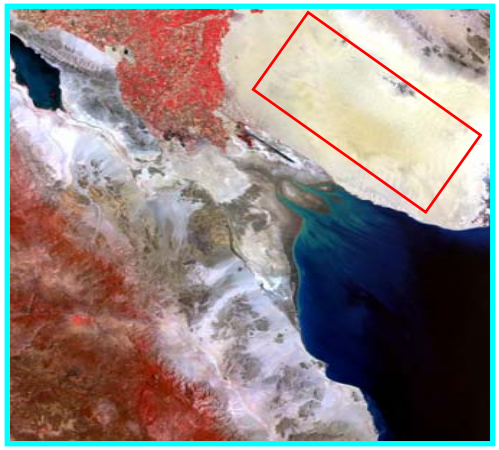
Sonora Desert

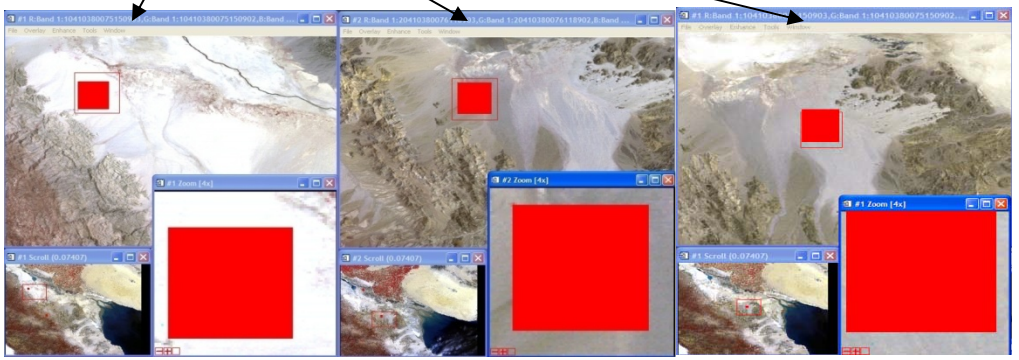
Methodology Update: Regions of Interest (L1—L2 example)

- Five pairs of near-coincident scenes from the Sonora Desert site are selected.
- In order to acquire a better regression line fit and to cover the wider dynamic range, additional ROIs were selected that had either a high, medium, or low reflectance value.

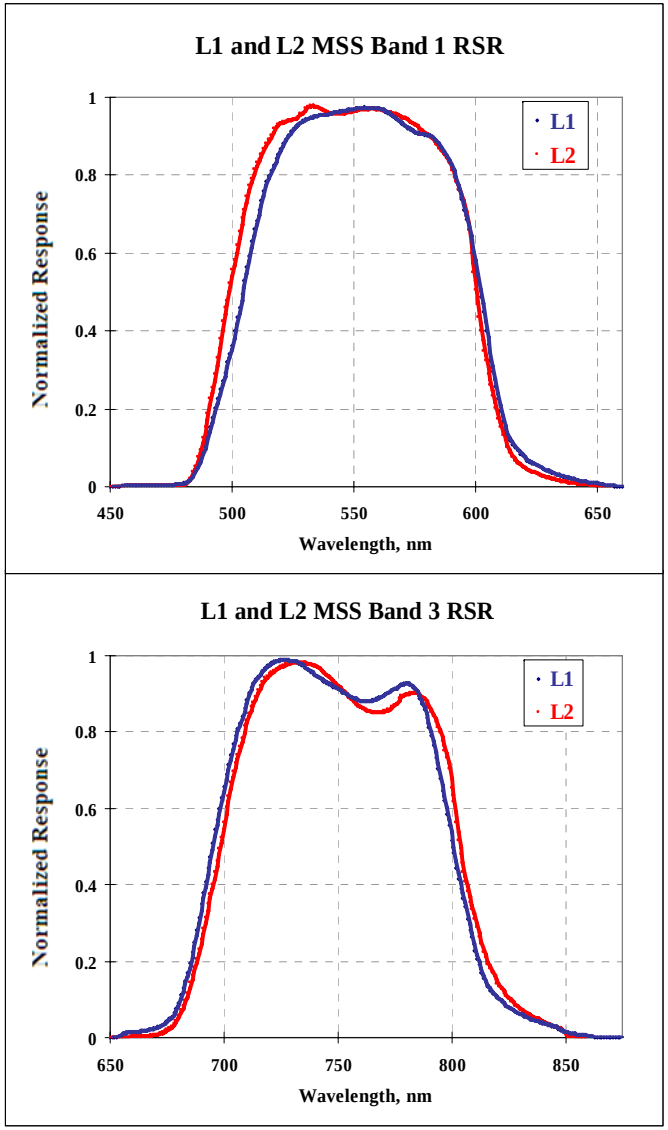
Scene Pair used 5	Total 22 ROIs
Scene Pair-1	LM10410381975150AAA04
	LM20410381975159AAA05
Scene Pair-2	LM10410381976073AAA02
	LM20410381976082AAA01
Scene Pair-3	LM10410381976109AAA02
	LM20410381976100AAA01
Scene Pair-4	LM10410381976289AAA04
	LM20410381976280AAA03
Scene Pair-5	LM10410381976109AAA02
	LM20410381976118AAA01

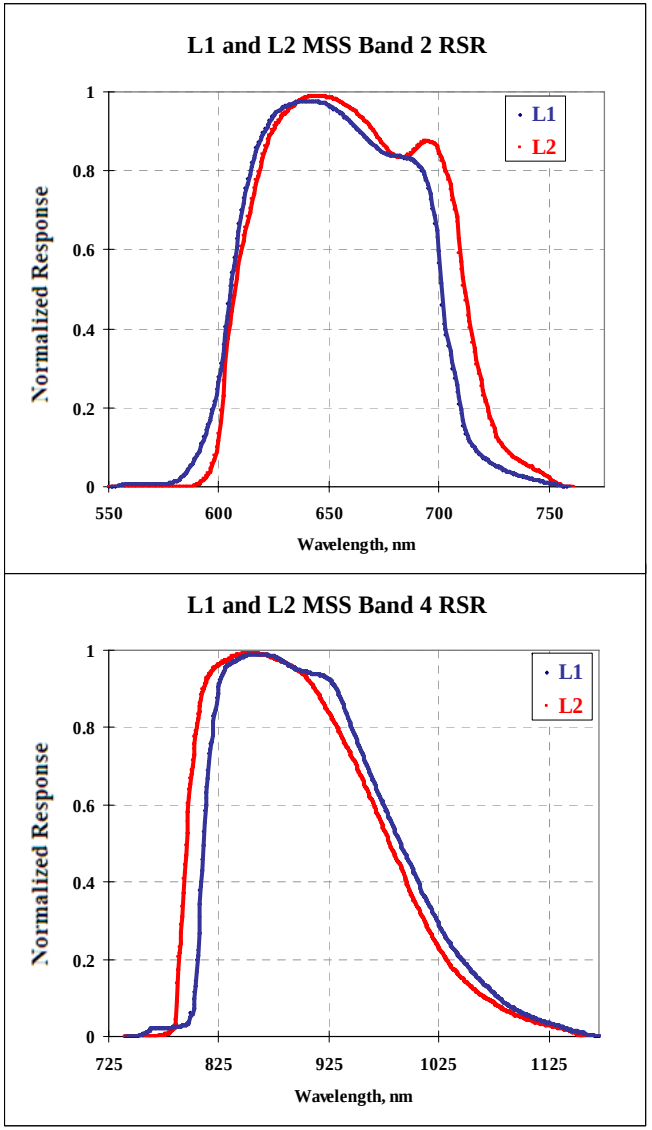
Updated: Additional ROIs and some more





Relative Spectral Response (RSR) Profiles of Landsats 1 & 2



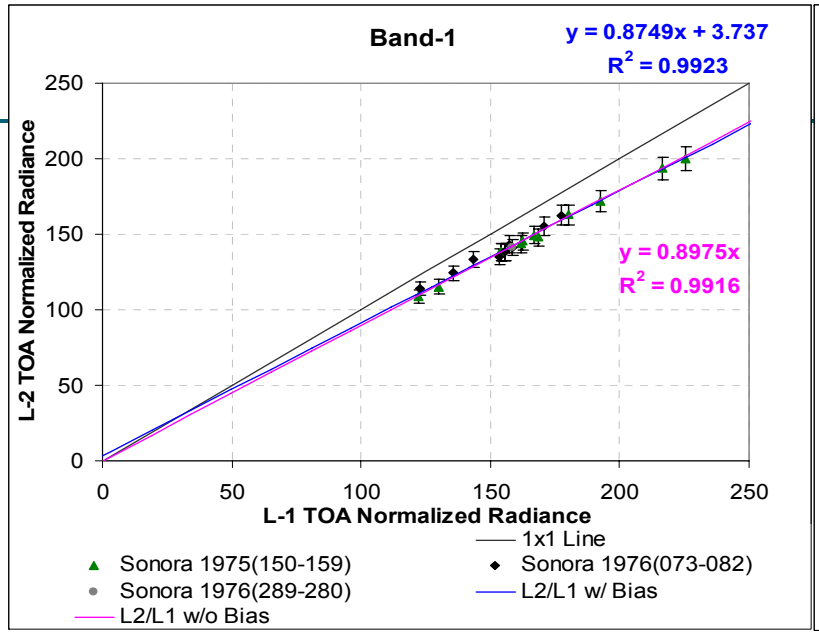


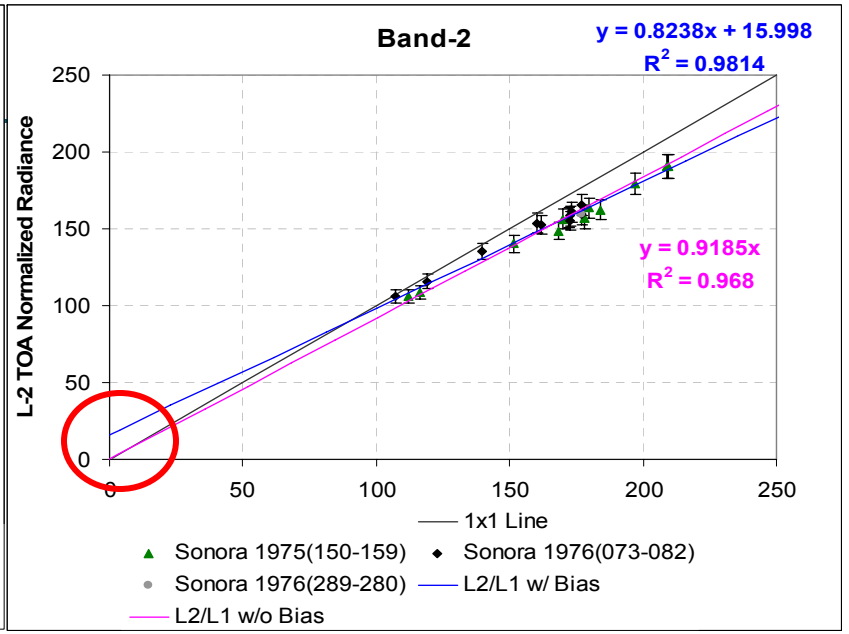
Uncertainty Estimates for the Landsat 1 to 2 Cross-calibration

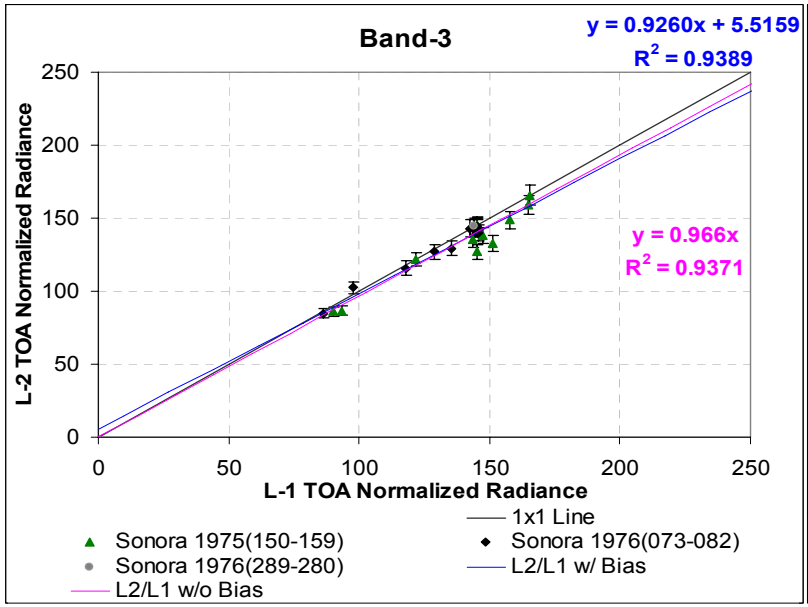
- Atmospheric effect: Atmospheric transfer model run over Landsat MSS.
- Filter spectral effect: Spectral Band difference Effects calculated using approximated ground target
- BRDF effect: Reference Slides “Landsat Invariant Site Calibration” by RIT, Cliff Anderson

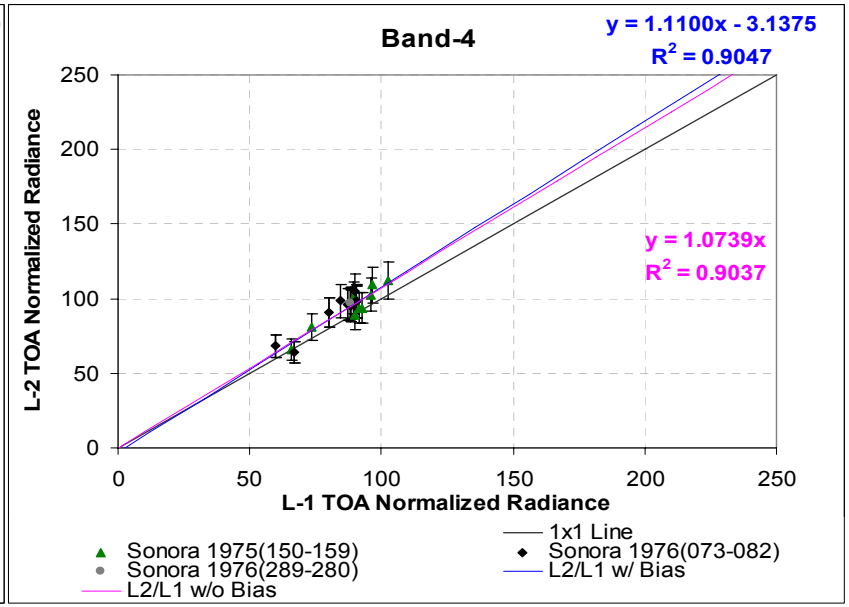
	Atmospheric Effect	SBAF	BRDF	Total Uncertainty estimates
Band-1	4.4%	0.7%	0.3%	~4.5%
Band-2	3.5%	1.1%	0.4%	~4%
Band-3	4.4%	0.5%	0.7%	~4.5%
Band-4	11.4%	0.5%	0.7%	~11%

Landsat 1 to 2 Cross-calibration Results









Statistical T-test Values for Distinguishing the Intercepts from Zero

H_0: Bias=0

with the 0.01 level of significance

Parameter Estimates for Xcal of L2 and L1

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3.7233788	2.840296	1.31	0.2047
Slope	0.8750346	0.017321	50.52	<.0001*

Parameter Estimates for Xcal of L2 and L1 (Band-2)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	15.994953	4.225016	3.79	0.0012*
Slope	0.8238099	0.025397	32.44	<.0001*

Band-2, Bias is NOT 0

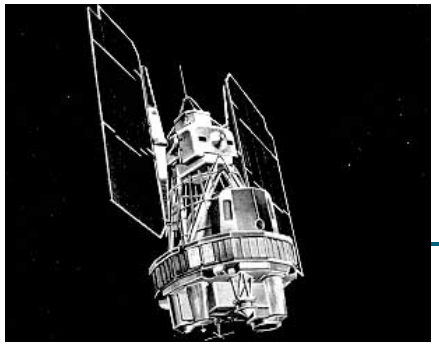
Parameter Estimates for Xcal of L2 and L1 (Band-3)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	5.5188043	7.370106	0.75	0.4631
Slope	0.9260072	0.054184	17.09	<.0001*

Parameter Estimates for Xcal of L2 and L1 (Band-4)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-3.136906	7.999168	-0.39	0.7005
Slope	1.110001	0.093025	11.93	<.0001*

- Statistical tests support that the bias term in the cross-calibration of Landsat 1 and 2 is not zero for Band 2.



Updated

Cross-calibration of Landsat 2 to 3 MSS

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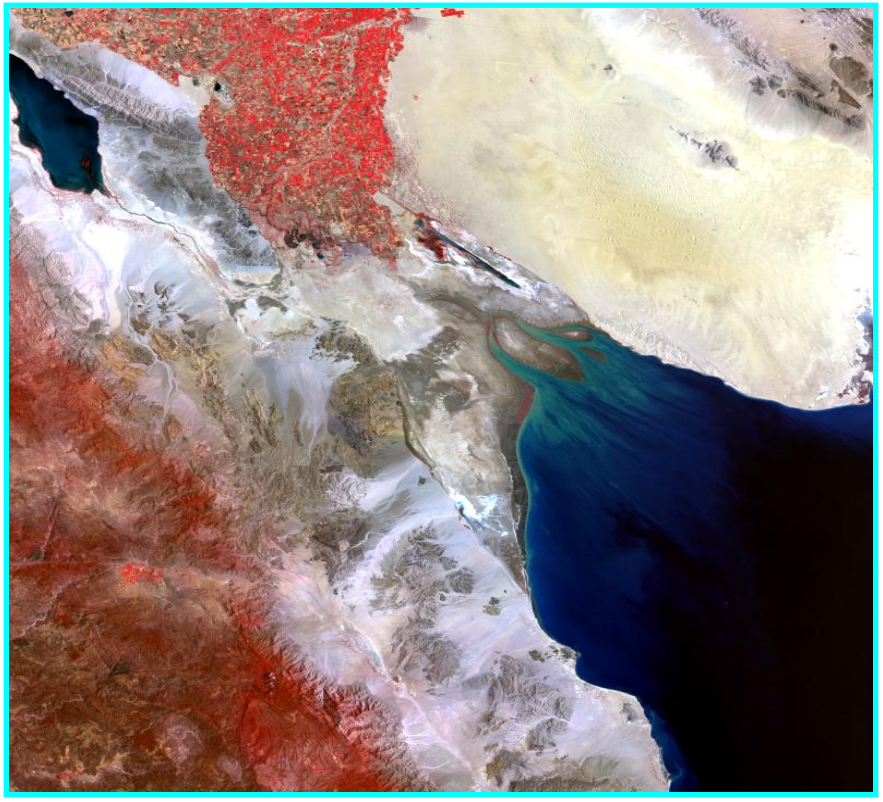
Site used for Cross-calibration of Landsat 2 to 3

Updated



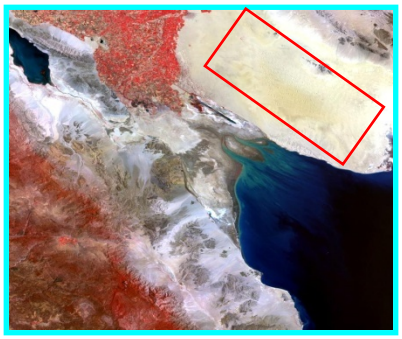
Sonora Desert

Regions of Interest

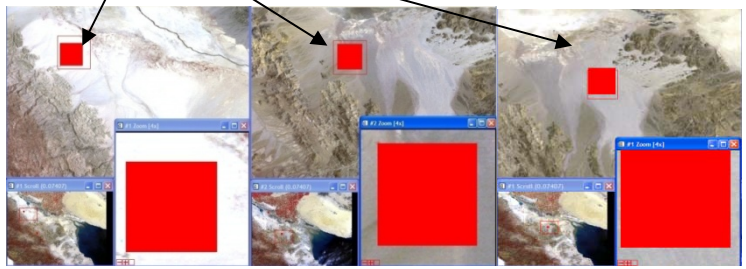
Updated

- Three pairs of near-coincident scenes from the Sonora Desert site are selected.
- ***Updated:***
  - To cover the wider dynamic range, additional ROIs were selected.
  - One additional format of MSS (i.e. MSS-P format data) is also added by this cross calibration method.

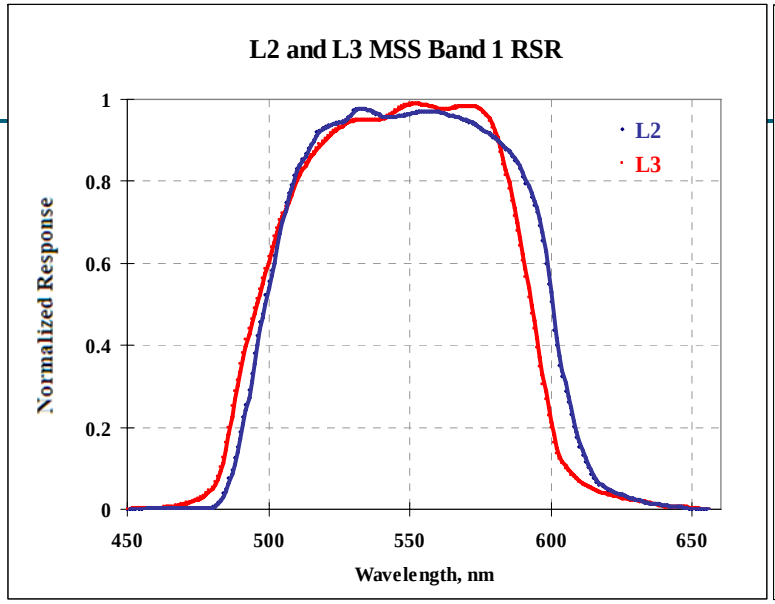
Scene Pair used 3	Total 23 ROIs
Scene Pair-1	LM20410381981073AAA03
	LM30410381981082AAA04
Scene Pair-2	LM20410381979300AAA03
	LM30410381979309AAA03
Scene Pair-3	LM20410381979138AAA03
	LM30410381979129AAA03

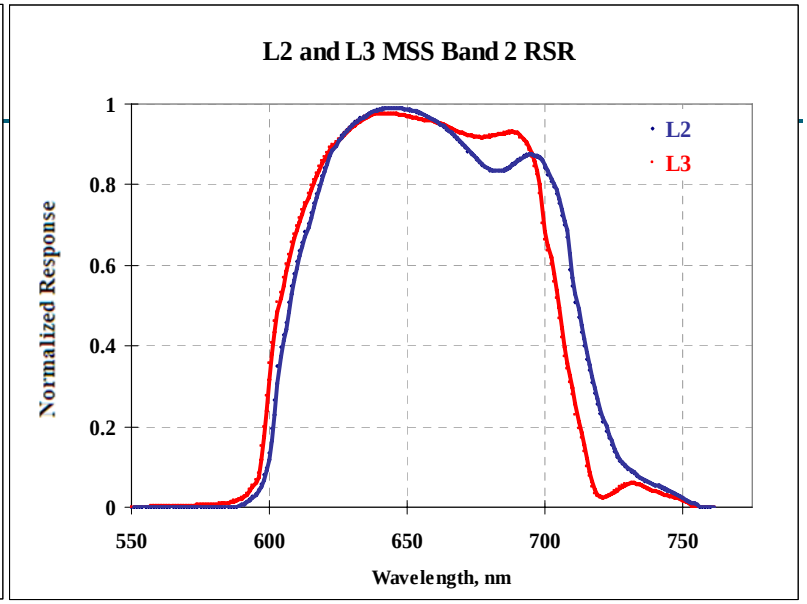


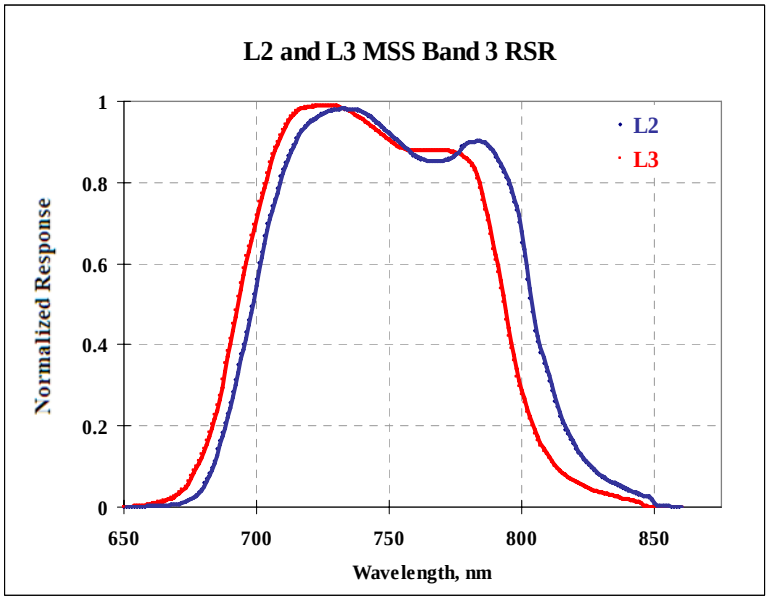
Updated: Additional ROIs and some more

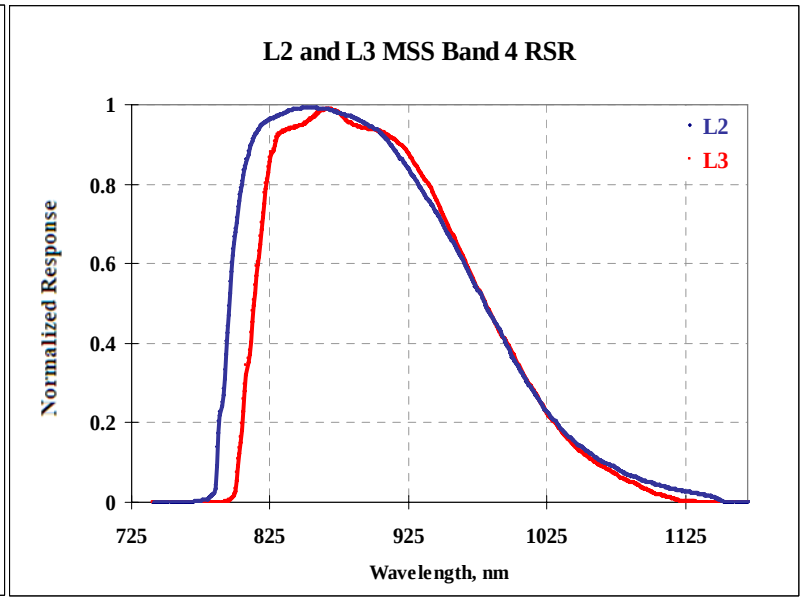


RSR Profiles of Landsats 2 & 3 *Updated*









Uncertainty Estimates for Landsat 2 to 3 Cross-calibration

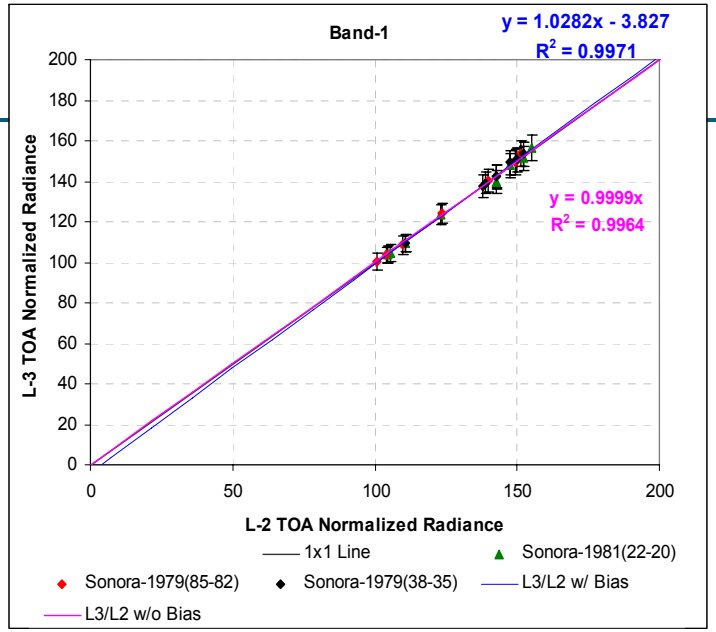
Updated

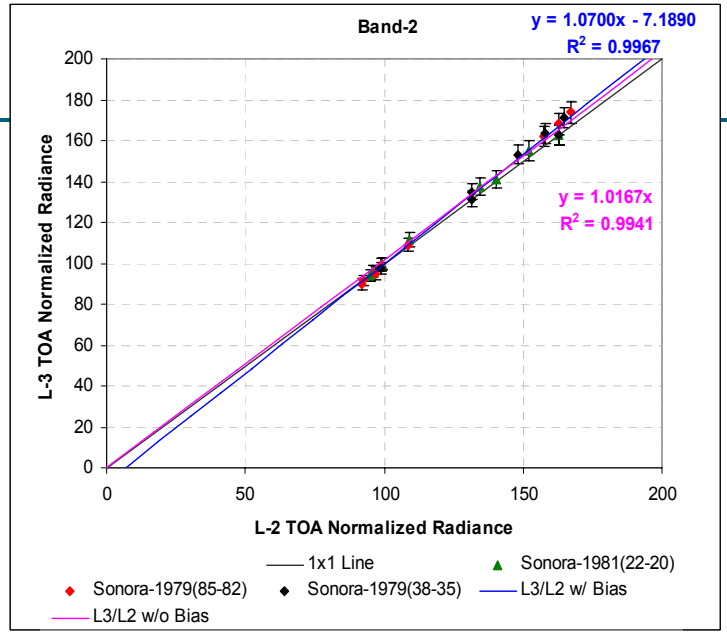
- Atmospheric effect
- BRDF effect
- Filter spectral effect

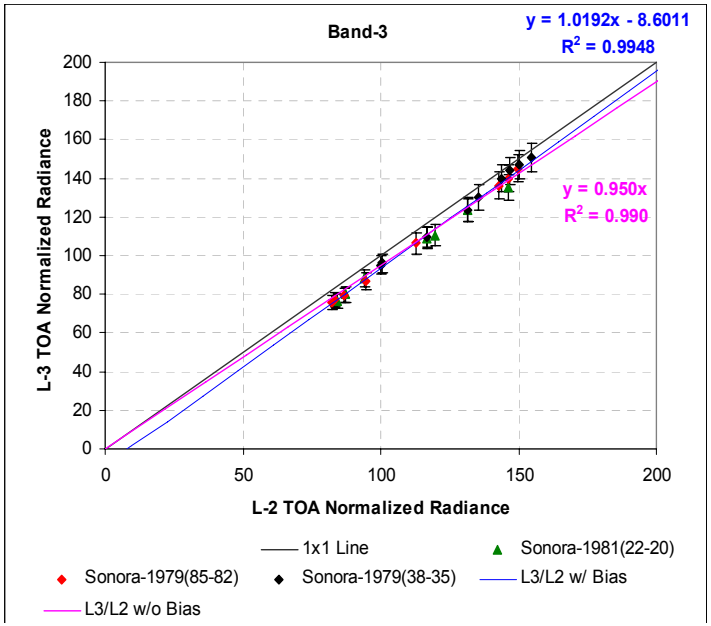
	Atmospheric Effect	SBAF	BRDF	Total Uncertainty estimates
Band-1	4.3%	1.1%	0.3%	~4%
Band-2	3.4%	0.8%	0.4%	~3%
Band-3	4.4%	1.4%	0.7%	~5%
Band-4	11.4%	0.3%	0.7%	~11%

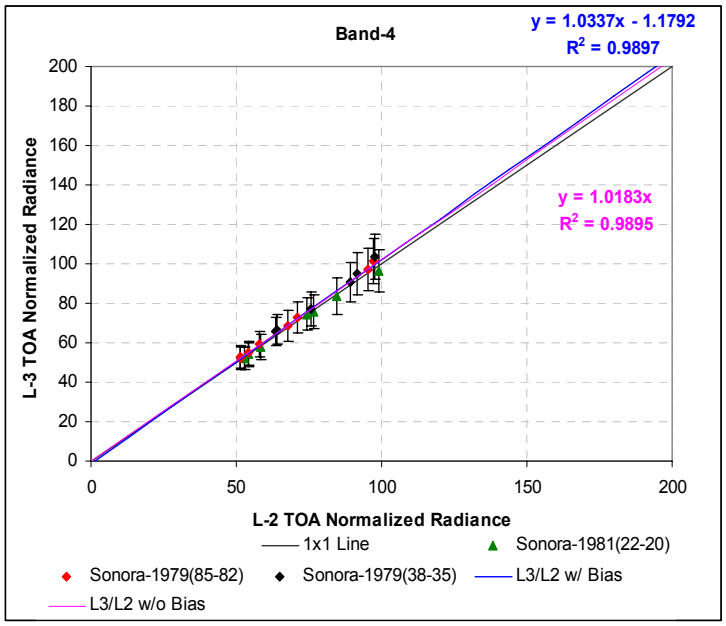
Landsat 2 to 3 Cross-calibration Results

Updated









Statistical T-test Values for Distinguishing the Intercepts from Zero

Updated

H_0: Bias=0

with the 0.01 level of significance

Parameter Estimates for Xcal of L3 and L2 (Band-1)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-3.907269	1.602489	-2.44	0.0237*
Slope	1.0288047	0.01199	85.81	<.0001*

Parameter Estimates for Xcal of L3 and L2 (Band-2)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-7.197208	1.766287	-4.07	0.0005*
Slope	1.0700121	0.013404	79.83	<.0001*

Band-2,Bias is NOT 0

Parameter Estimates for Xcal of L3 and L2 (Band-3)

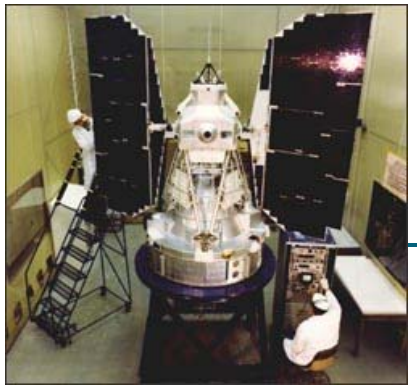
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-8.638022	1.9025	-4.54	0.0002*
Slope	1.0196356	0.015635	65.21	<.0001*

Band-3, Bias is NOT 0

Parameter Estimates for Xcal of L3 and L2 (Band-4)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.082715	1.805562	-0.60	0.5558
Slope	1.032722	0.024218	42.64	<.0001*

- Statistical tests support that the bias term in the cross-calibration of Landsat 2 and 3 is not zero for Band 2 and Band 3.



Cross-calibration of Landsat 3 to 4 MSS

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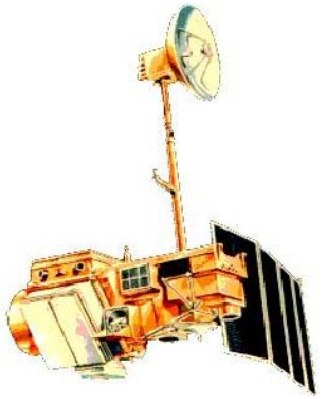
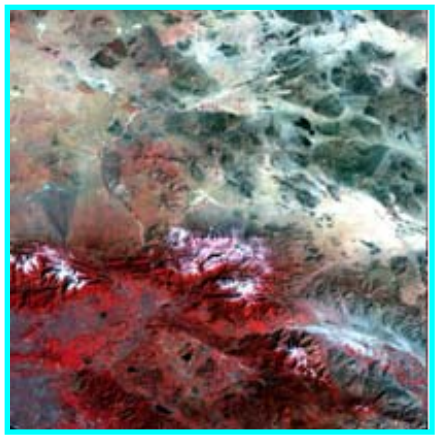


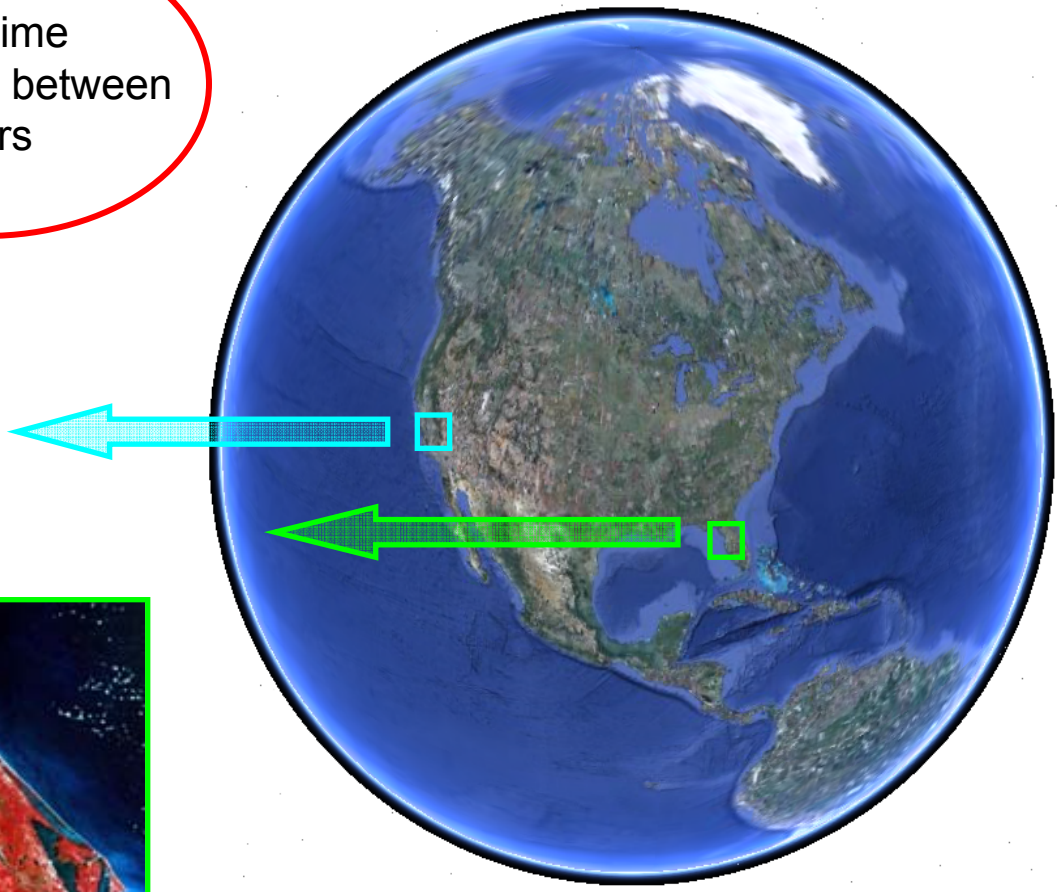
Sites used for Cross-calibration of Landsat 3 to 4

4 minute time difference between scene-pairs



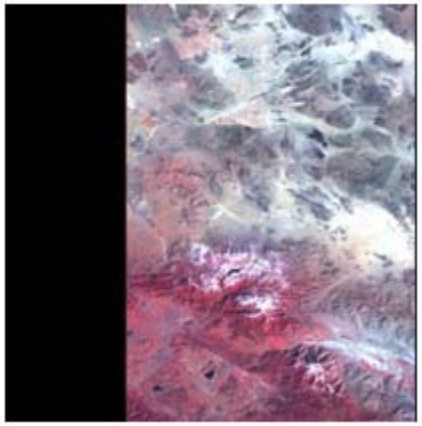
California

Florida

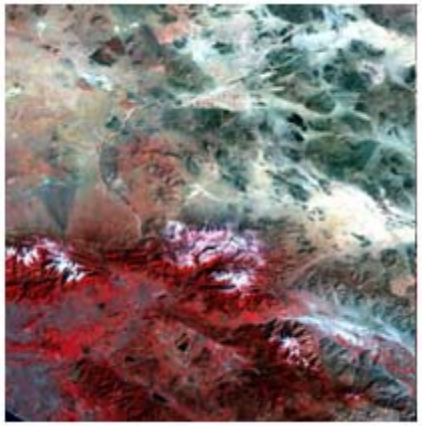


Background

- The different temporal resolutions (WRS-1 vs. WRS-2) of Landsats 3 and 4 allowed the two satellites to follow a nearly synchronous orbital path on January 20, 1983.
- Two pairs of good scenes are selected from this dataset to cross-compare the responses of Landsats 3 and 4.



LM30430361983020AAA03
1983:020:17:47:04



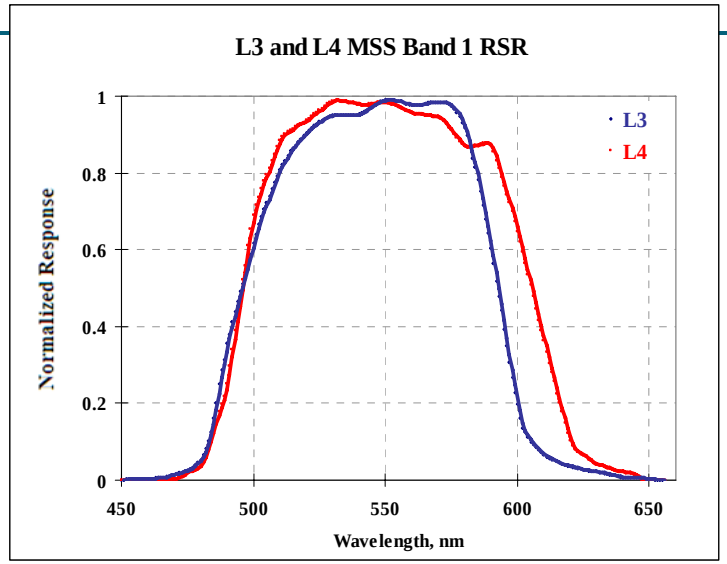
LM40400361983020AAA03
1983:020:17:51:00

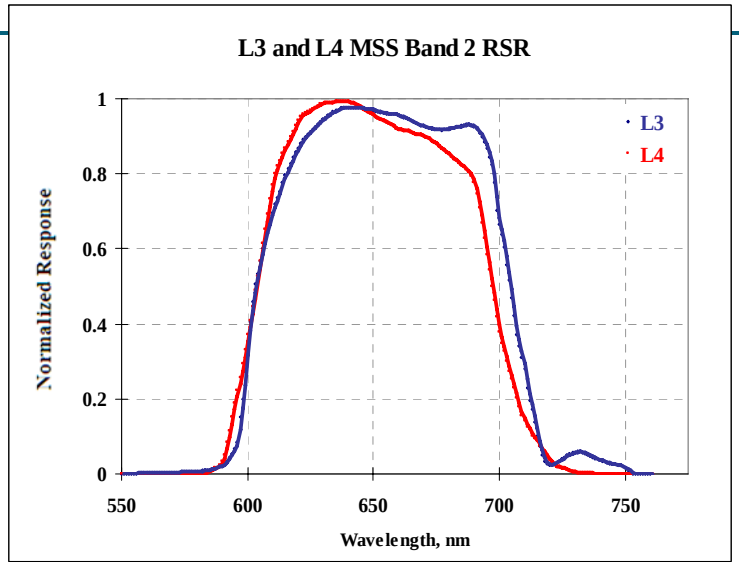
LM30170401983012AAA03
1983:012:15:20:00

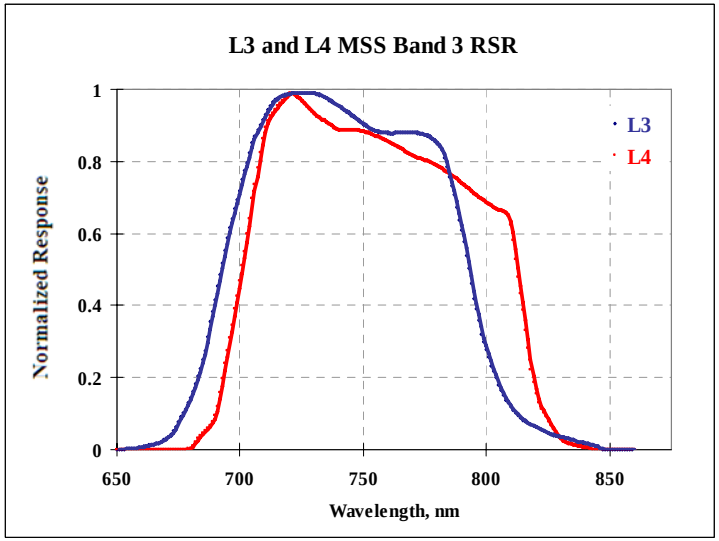
LM40160401983012AAA03
1983:012:15:24:00

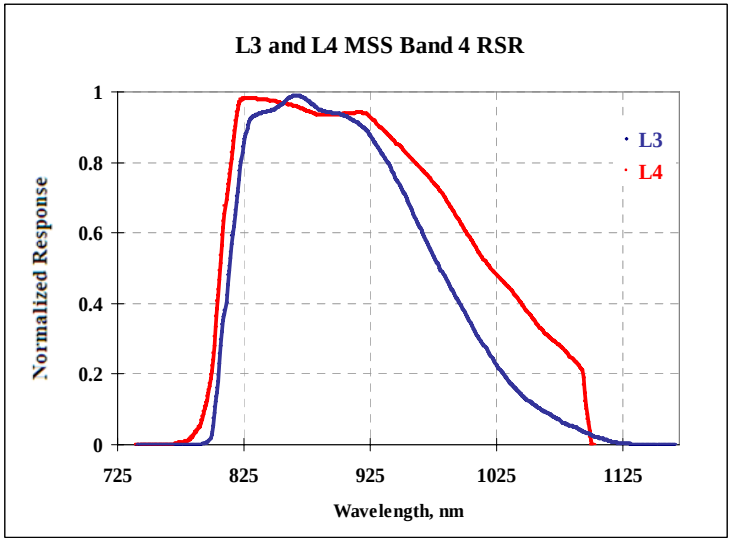
Altogether, eight ROIs were defined in homogeneous areas throughout the scene pairs.

RSR Profiles of Landsats 3 & 4









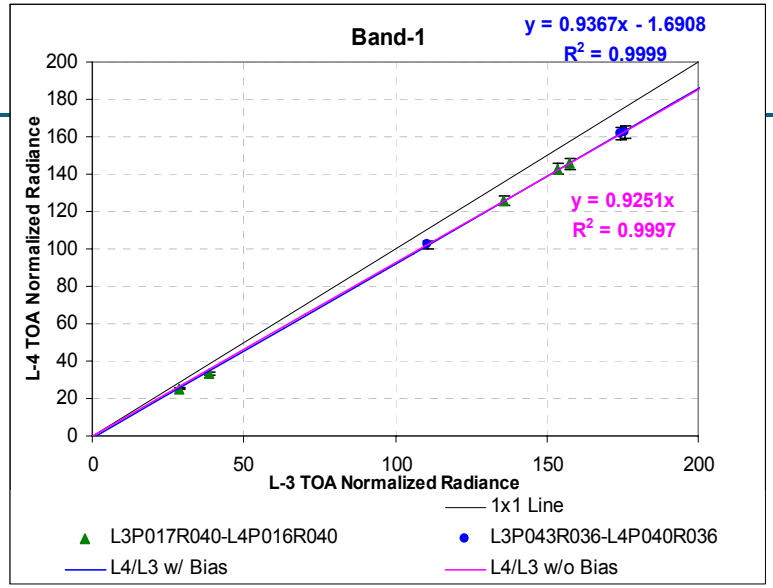
Uncertainty Estimates for Landsat 3 to 4 Cross-calibration

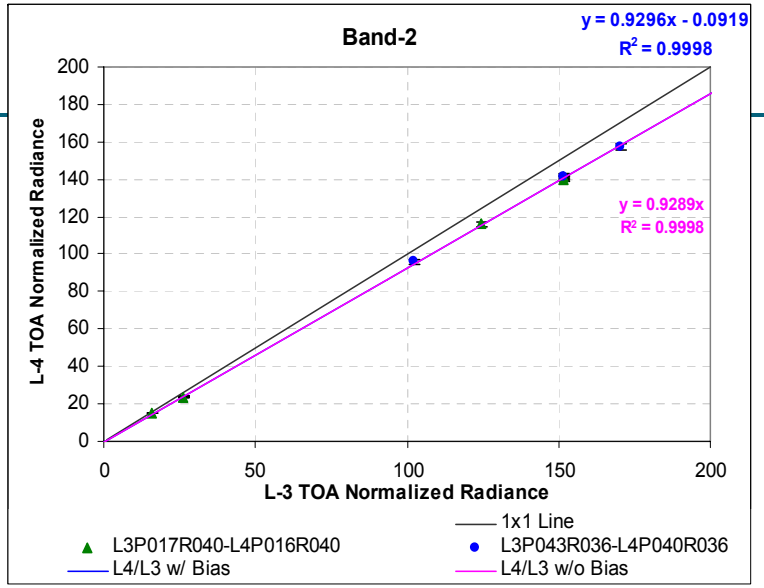
- Atmospheric effect
- BRDF effect
- Filter spectral effect

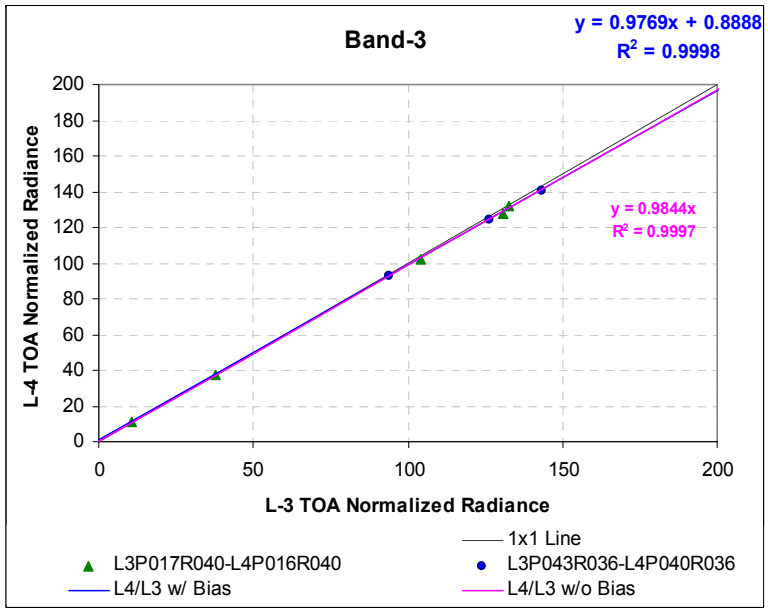
	Atmospheric Error	SBAF	BRDF	Total Uncertainties estimates
Band-1	0.0%	1.6%	0.3%	~2%
Band-2	0.0%	0.7%	0.4%	~1%
Band-3	0.0%	1.2%	0.7%	~1%
Band-4	0.0%	1.3%	0.7%	~1%

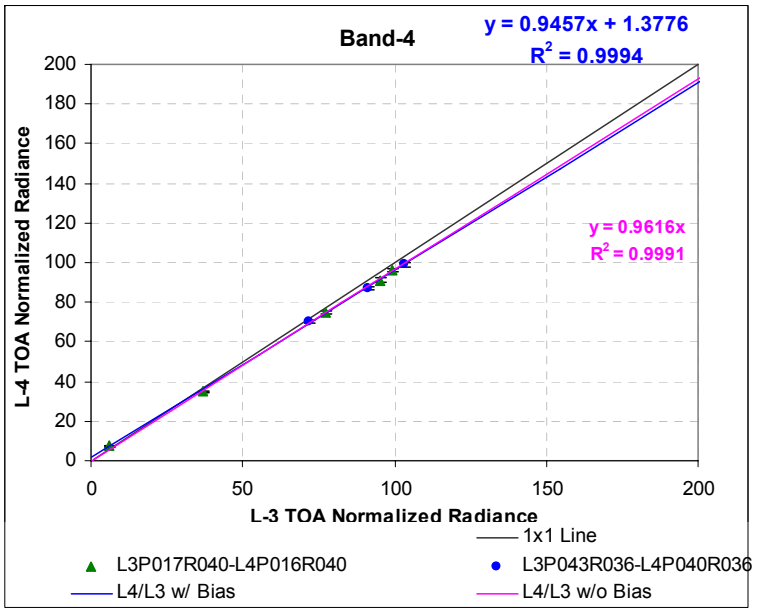
Since the scene pairs used for the cross-calibration has a 4-minute time difference, atmospheric errors are zeroed.

Landsat 3 to 4 Cross-calibration Results









Statistical T-test Values for Distinguishing the Intercepts from Zero

H_0: Bias=0

with the 0.01 level of significance

Parameter Estimates for Xcal of L3 and L24(Band-1)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.702134	0.494494	-3.44	0.0138*
Slope	0.9368127	0.003702	253.02	<.0001*

Parameter Estimates for Xcal of L3 and L4 (Band-2)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.088046	0.499295	-0.18	0.8650
Slope	0.9296013	0.004228	219.88	<.0001*

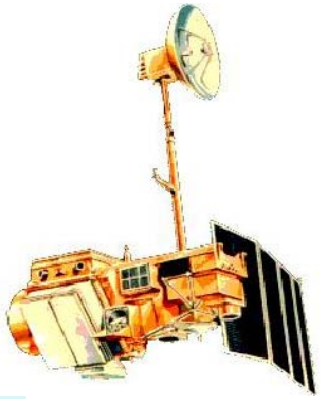
Parameter Estimates for Xcal of L3 and L4(Band-3)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.9109056	0.582673	1.56	0.1690
Slope	0.976817	0.005423	180.12	<.0001*

Parameter Estimates for Xcal of L3 and L4(Band-4)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.3950443	0.761196	1.83	0.1166
Slope	0.9455165	0.00958	98.70	<.0001*

- Statistical tests support that the bias term in the cross-calibration of Landsat 3 and 4 is zero for all bands at the 0.01 level of significance.



Cross-calibration of Landsat 4 to 5 MSS

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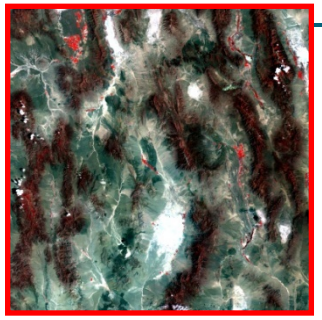
Sites used for Cross-calibration of Landsat 4 to 5 MSS

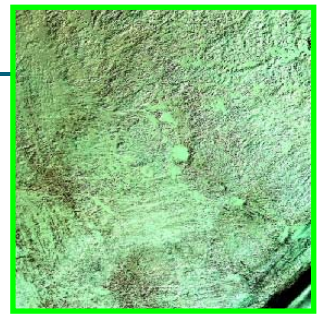


Rail Road Valley

Ivanpah Playa

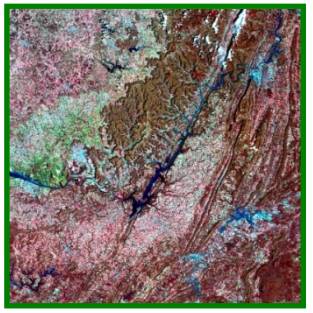
Sonora Desert

White Sand



Quebec, Canada

Previously



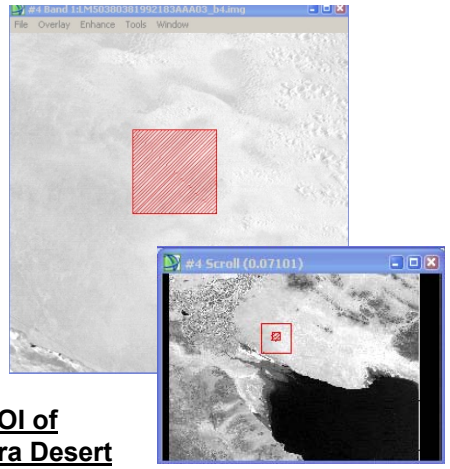
Huntsville, Alabama

Updated

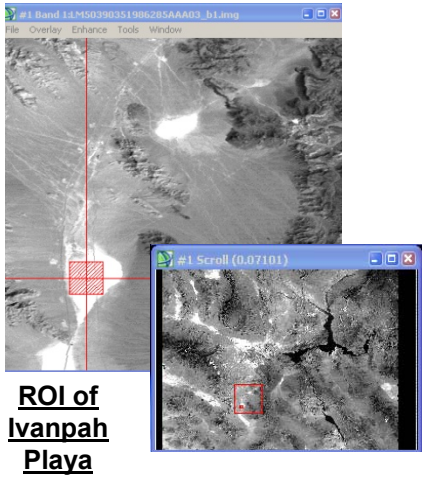
Background

- Immediately after launch, Landsat 5 was initially placed in a tandem orbit with Landsat 4 for a near-simultaneous data acquisition for direct comparison.
- Two good scene-pairs were selected from this dataset to compare the responses of Landsats 4 and 5.
- In addition to the same-day scene pairs, the cross-calibration of Landsats 4 and 5 also used four nearly co-incident scenes pairs to find any temporal changes within the system during it's active lifetime.

Scene pairs used 6	Total 36 ROIs	
Rail Road Valley	LM40400331992205AAA03	9 Days apart
	LM50400331992213AAA03	
Ivanpah Playa	LM40390351986277AAA03	9 Days apart
	LM50390351986285AAA03	
White Sand	LM40330371992188AAA03	9 Days apart
	LM50330371992180AAA03	
Sonora Desert	LM40380381992159AAA03	24 Days apart
	LM50380381992183AAA03	
Quebec, Canada	LM40200181984075AAA04	2 second apart
	LM50200181984075AAA03	
Huntsville, Alabama	LM40200361984075AAA04	2 second apart
	LM50200361984075AAA03	

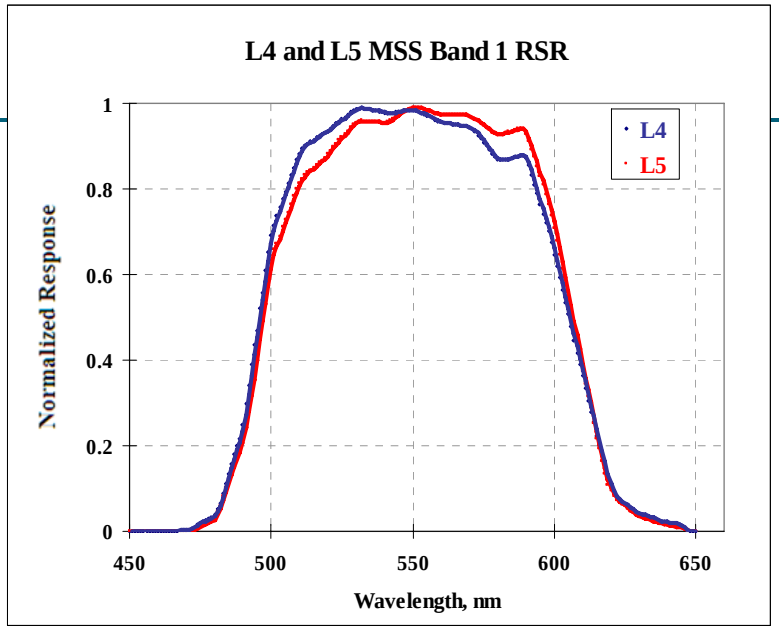


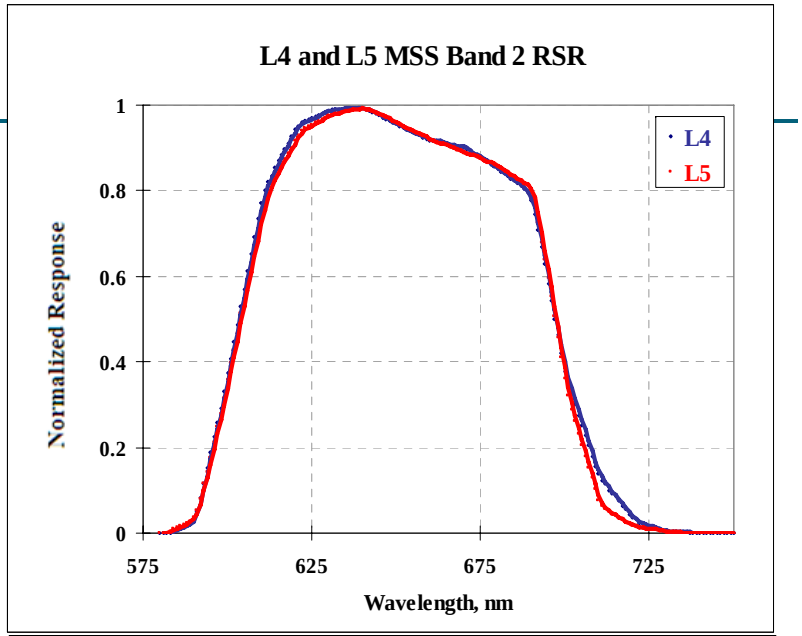
ROI of Sonora Desert

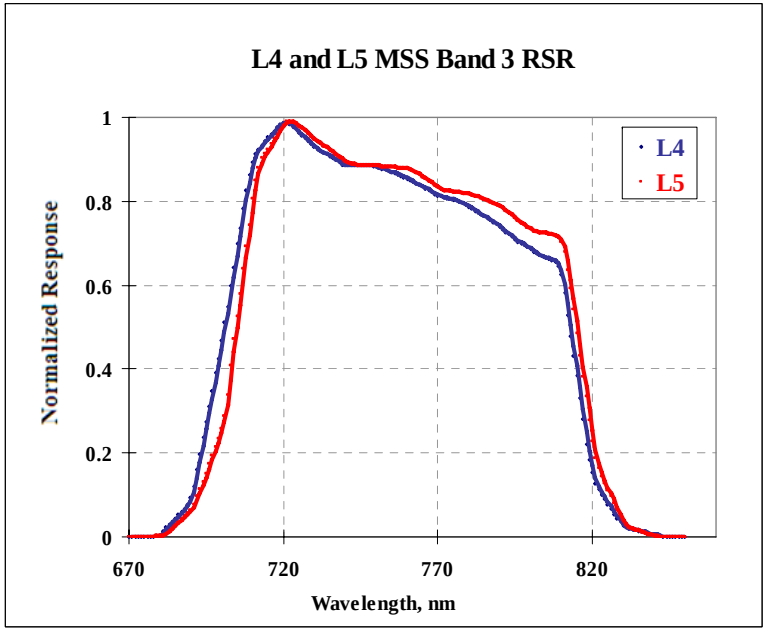


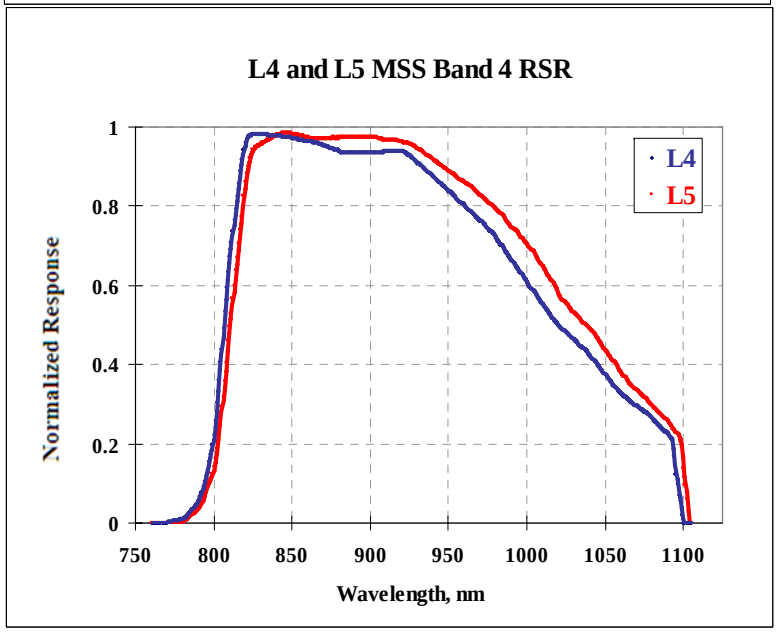
ROI of Ivanpah Playa

RSR Profiles of Landsats 4 & 5







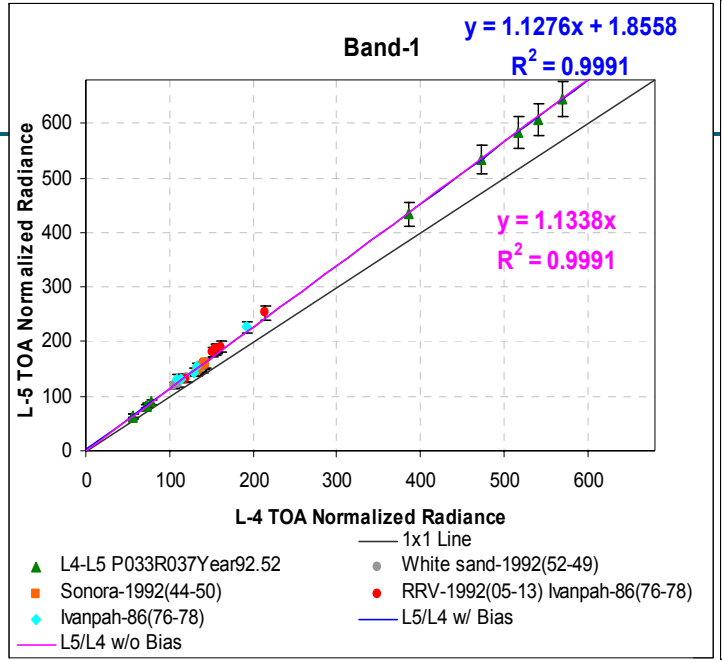


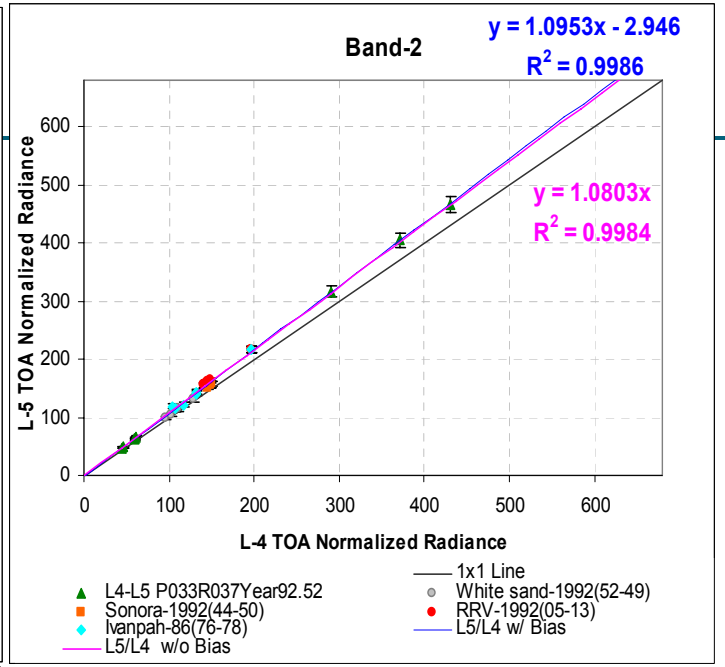
Uncertainty Estimates for Landsat 4 to 5 Cross-calibration

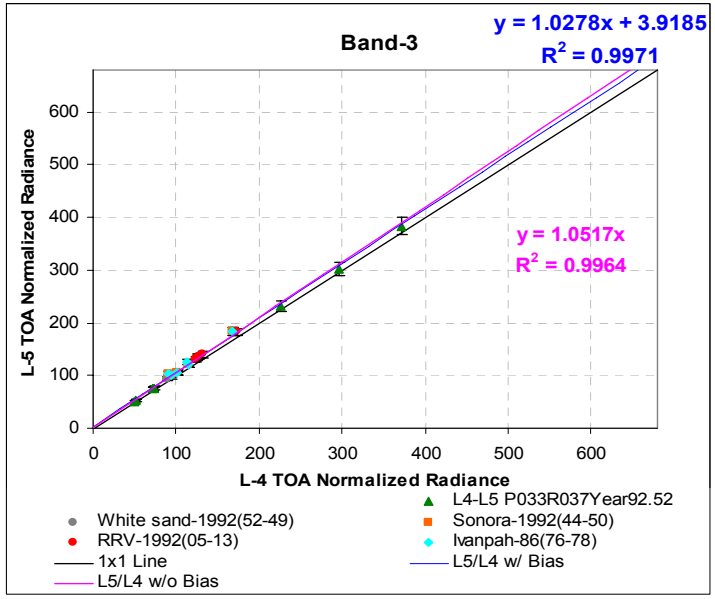
- Atmospheric effect
- BRDF effect
- Filter spectral effect

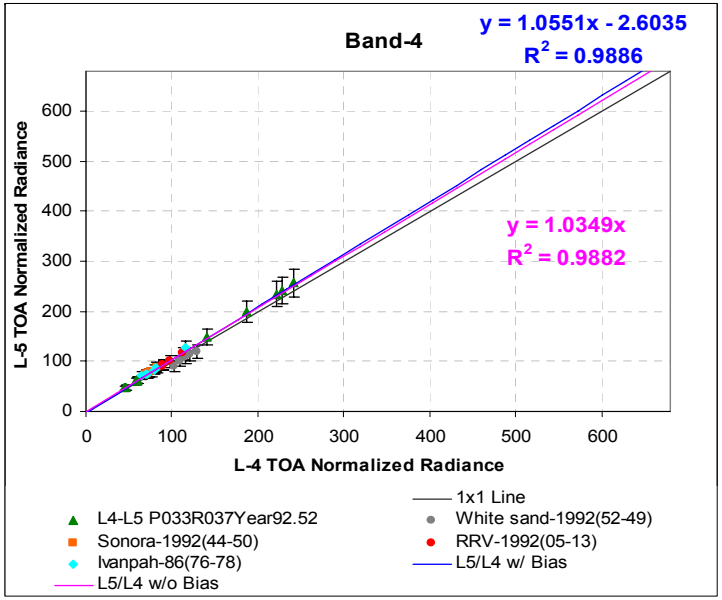
	Atmospheric Error	SBAF	BRDF	Total Uncertainties estimates
Band-1	4.47%	0.61%	0.3%	~5%
Band-2	3.42%	0.12%	0.4%	~3%
Band-3	4.38%	0.70%	0.7%	~4%
Band-4	11.36%	0.69%	0.7%	~11%

Landsat 4 to 5 Cross-calibration Results









Statistical T-test Values for Distinguishing the Intercepts from Zero

H_0: Bias=0

with the 0.01 level of significance

Parameter Estimates for Xcal of L4 and L5 (Band-1)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.8574767	1.462157	1.27	0.2141
Slope	1.1275531	0.006248	180.45	<.0001*

Parameter Estimates for Xcal of L4 and L5 (Band-2)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-2.946368	1.328228	-2.22	0.0351*
Slope	1.0953493	0.007879	139.01	<.0001*

Parameter Estimates for Xcal of L4 and L5 (Band-3)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3.9189815	1.555178	2.52	0.0182*
Slope	1.0278279	0.010822	94.97	<.0001*

Parameter Estimates for Xcal of L4 and L5 (Band-4)

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-2.601476	2.418215	-1.08	0.2909
Slope	1.0551365	0.021009	50.22	<.0001*

- Statistical tests support that the bias term in the cross-calibration of Landsat 4 and 5 is zero for all bands at the 0.01 level of significance.

Cross-calibration Summary

Cross-calibration Equation:

$$L_{\lambda}(L_{n+1}) = G_{n,n+1} \times L_{\lambda}(L_n) + b_{n,n+1}$$

Cross Calibration Gains and Biases between the Landsat MSS Sensors					
Landsat 1 to Landsat 2			Landsat 2 to Landsat 3		
	Gain	Bias		Gain	Bias
Band 1	0.8975	0	Band 1	0.9999	0
Band 2	0.8238	15.998	Band 2	1.0700	-7.189
Band 3	0.9660	0	Band 3	1.0192	-8.6011
Band 4	1.0739	0	Band 4	1.0183	0
Landsat 3 to Landsat 4			Landsat 4 to Landsat 5		
	Gain	Bias		Gain	Bias
Band 1	0.9251	0	Band 1	**1.1338**	0
Band 2	0.9289	0	Band 2	1.0803	0
Band 3	0.9844	0	Band 3	1.0517	0
Band 4	0.9616	0	Band 4	1.0349	0

- Two bias terms for Band 2 and one bias term for Band 3.

Final Equation for Cross-calibrating each MSS Normalized Radiance to Landsat 5 MSS

The final equation is

$$L_{\lambda}(L_5) = G_{n,5} \times (TDF) \times L_{\lambda}(L_n) + b_{n,5}$$

where,

$L_{\lambda}(L_5)$ = L_5 MSS mapped radiance value *(units: W/m² sr µm)*

$G_{n,5}$ = cross-calibration gain between given band and MSS sensor and L5 MSS *(unitless)*

$L_{\lambda}(L_n)$ = original radiance value of Landsat 'n' MSS *(units: W/m² sr µm)*

$b_{n,5}$ = cross-calibration band offset from L5 MSS *(units: W/m² sr µm)*

TDF = time dependant factor (explained in next slides)

Time Dependent Factors (TDF)

To account for change in gain over the mission lifetime, a time-dependent factor (TDF) term was added to the final cross-calibration equation. This TDF factor is defined as

$$TDF = \frac{C}{A \times (T - T_{Launch}) + B}$$

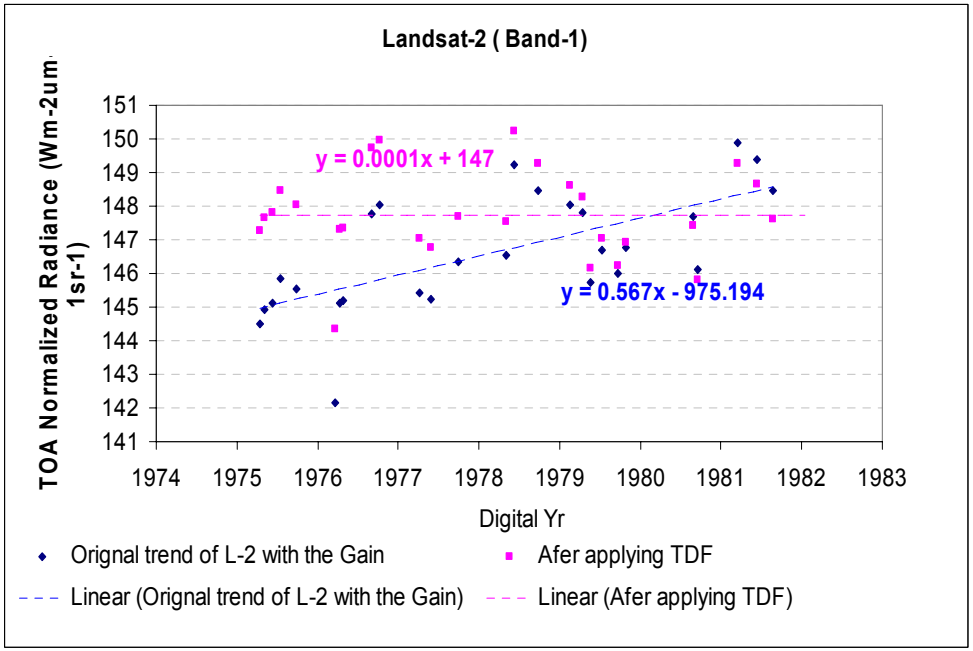
Where,
C = normalized radiance of the reference PICS at the cross-cal time point *(units: W/m² sr μm)*
T = scene acquisition date *(units: Decimal years)*
T_Launch = satellite launch date *(units: Decimal years)*
A = regression slope of the gain vs. time model *(units: W/(m² sr μm Decimal_years))*
B = bias derived from the regression offset of the gain vs. time model *(units: W/m² sr μm)*

Example: Time Dependent Factor (TDF) Calculations

Assumption: The temporal gain change for Landsat 2 (L2) MSS is characterized through apparent change in radiance of the reference calibration site as

L2 = 0.567 * T - 975.194

If the cross-calibration point for L2 MSS and L3 MSS is 1980.13 years and launch date of Landsat 2 is 1975.06 years, then



A = 0.567 *W/(m² sr µm Decimal_years)*
B = 0.567 * 1975.06 - 975.194
= 144.85 *W/m² sr µm*
C = 0.567 * (1980.13) - 975.194
= 147.72 *W/m² sr µm*

$$TDF = \frac{C}{A \times (T - T_{Launch}) + B}$$

$$TDF_{Landsat-2(Band-1)} = \frac{147.72}{0.567 \times (T - 1975.06) + 144.85}$$

Equivalent Landsat 5 MSS Radiance Conversion Factors for Landsats 1 through 4 MSS

Landsat 1				Landsat 2			
Band	Gain	Time Dependent Factor	Bias	Band	Gain	Time Dependent Factor	Bias
1	0.9837	1	0	1	1.0806	$\frac{147.72}{(0.567092*(T-TLaunch_2)+144.85)}$	0
2	0.8951	1	9.9635	2	1.0737	$\frac{170.85}{(0.53916*(T-TLaunch_2)+168.11)}$	-7.2141
3	1.0193	1	-8.9049	3	1.0552	1	-8.9049
4	1.0883	1	0	4	1.0134	1	0
Landsat 3				**Landsat 4**			
Band	Gain	Time Dependent Factor	Bias	Band	Gain	Time Dependent Factor	Bias
1	1.0489	$\frac{151.55}{(1.5251*(T-TLaunch_3)+144.10)}$	0	1	1.1338	1	0
2	1.0035	1	0	2	1.0803	1	0
3	1.0353	1	0	3	1.0517	1	0
4	0.9952	1	0	4	1.0349	1	0

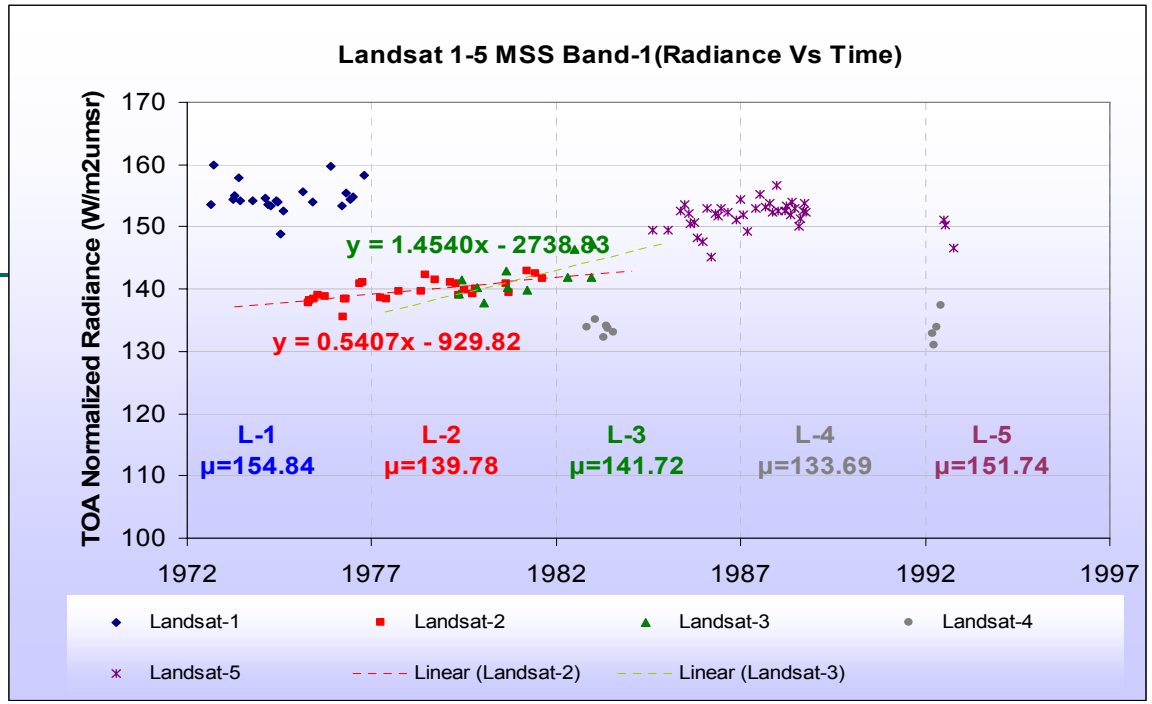
- ***All together there are four bias terms and three time dependent factors.***

Validation

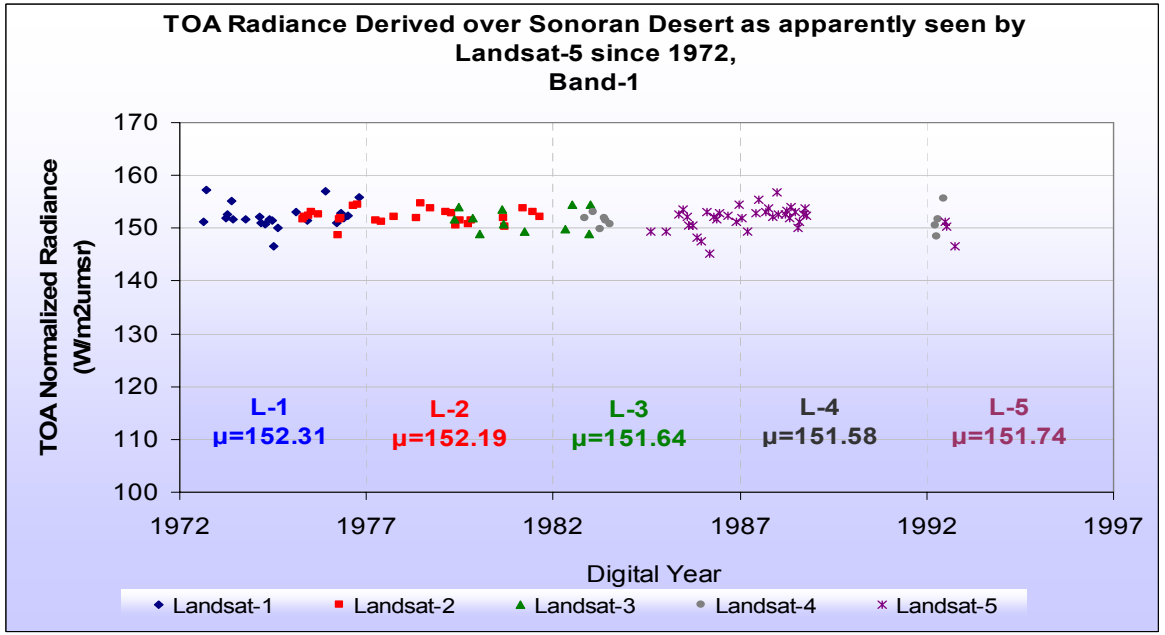
- Due to it's temporal invariance, the Sonora Desert site was selected for the validation of the cross-calibration results.
- In order to perform the validation of the cross-calibrations, the following assumptions must be made:
  - The Sonora Desert site is stable from 1972 to 1992.
  - Any genuine trend observed in the instrument response to this site is the characteristics of the instrument itself.
- Landsats 1 through 4's MSS data from Sonora desert were transformed to apparent Landsat 5 data using the cross-calibration connections established in the previous part of this presentation.
- Time factors were introduced in the cross-calibration results of Landsat 2 (Bands 1 and 2), and Landsat 3 (Band 1) to account for the regression trends illustrated in the lifetime responses to the Sonora Desert test site.

Band 1

Before cross-calibration applied

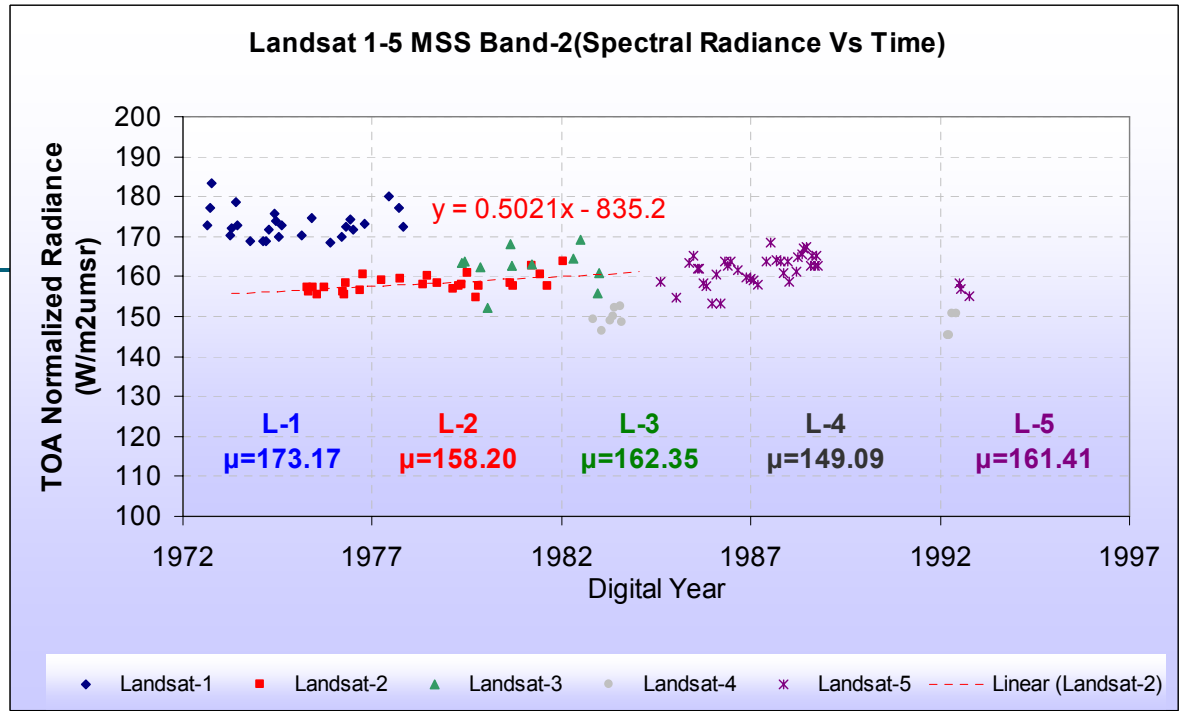


After cross-calibration applied

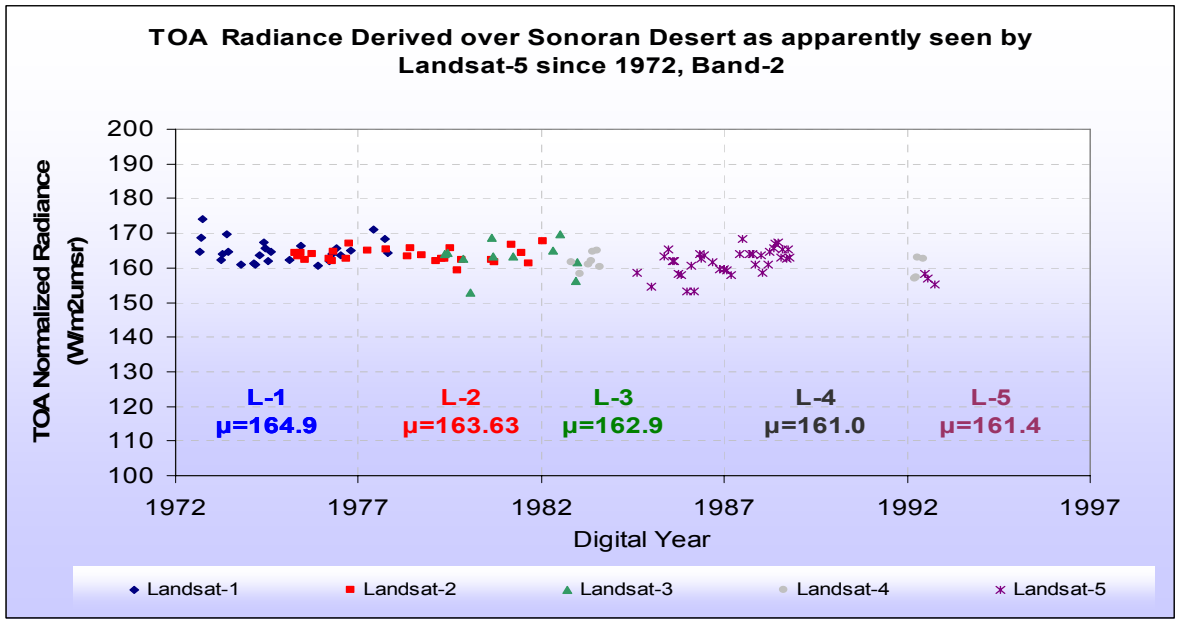


Band 2

Before cross-calibration applied

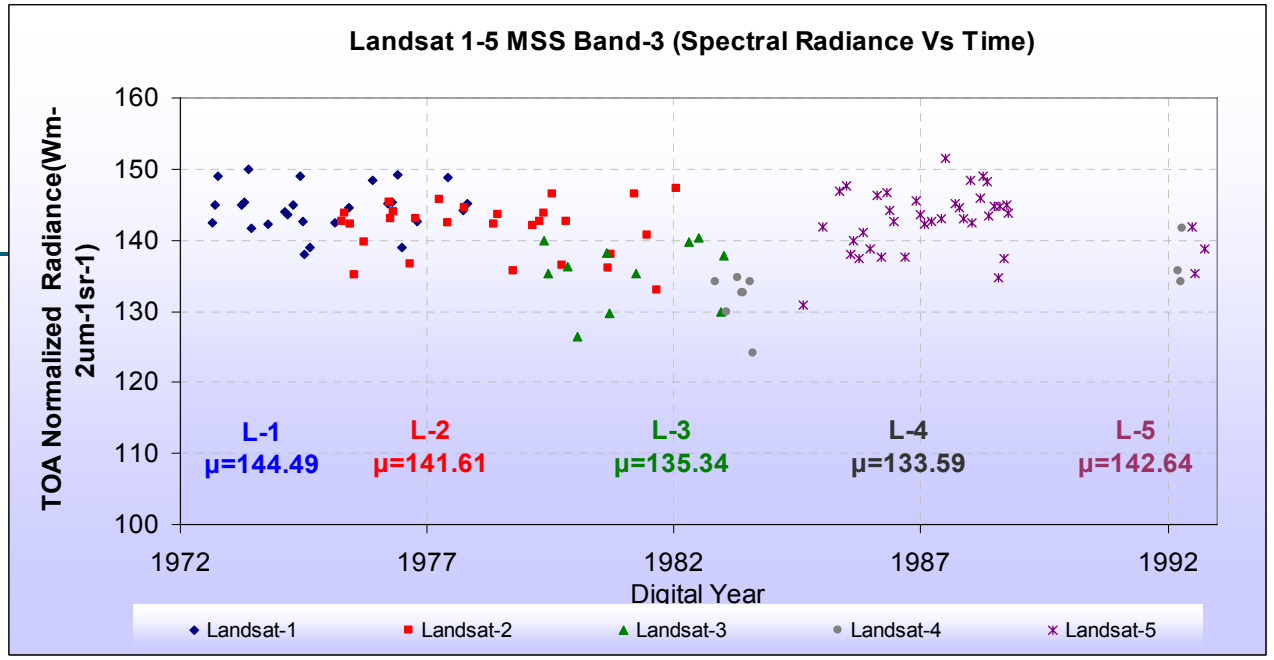


After cross-calibration applied

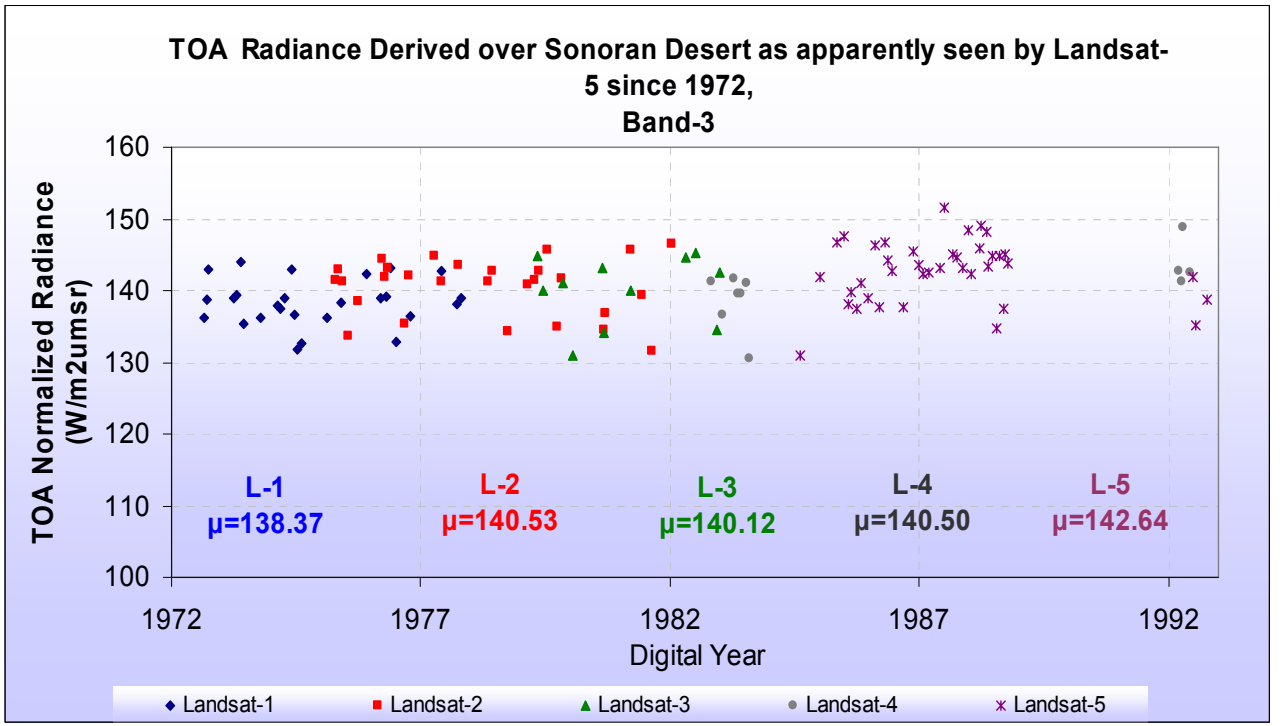


Band 3

Before cross-calibration applied

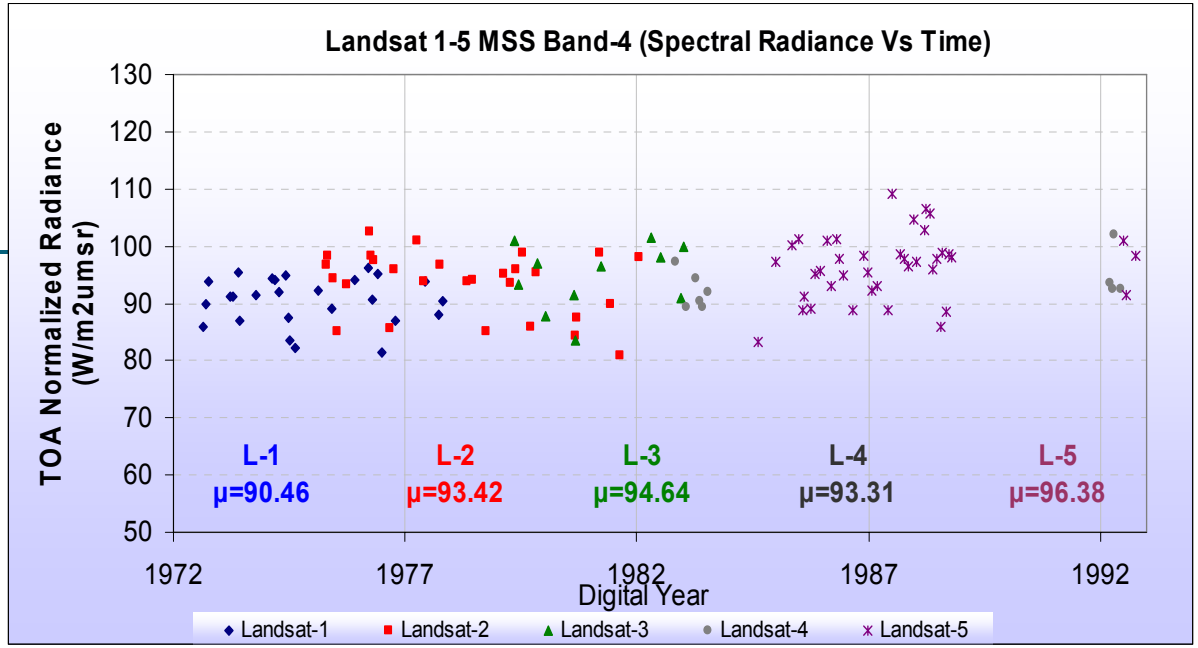


After cross-calibration applied

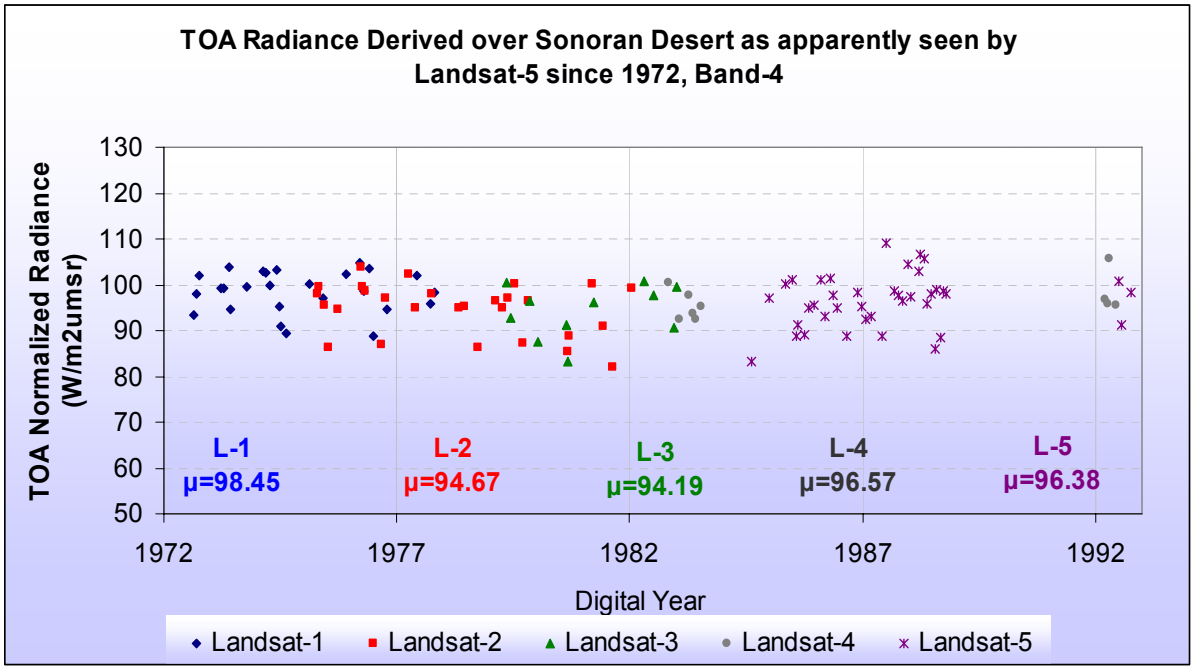


Band 4

Before cross-calibration applied



After cross-calibration applied



Summary of MSS Cross-calibration Revisited

Absolute Calibration Differences

	Before Calibration	After Calibration	
		(TOA Reflectance Space) (Previous method)	(TOA Radiance Space) Updated method
Band 1	16%	2%	**Less than 1%**
Band 2	17%	3%	**2%**
Band 3	8%	3%	**3%**
Band 4	11%	6%	**5%**

Final Lmin – Lmax Recommendation for MSS Imagery

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Outline

- Introduction
- The MSS Lmin-Lmax issue
- Absolute gain adjustments
- The MSS cross-calibration
- The time dependent factor (TDF) adjusted bands
- Dealing with an 8-bit product
- Solutions

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Introduction

- $LMIN_{\lambda}$ is the spectral radiance at $Q_{CAL} = 0$
- $LMAX_{\lambda}$ is the spectral radiance at $Q_{CAL} = Q_{CALMAX} = 127$ (in the case of 7-bit MSS)
- This 0 to 127 digital number range contains the allowable range of spectral radiance that the MSS sensors were able to acquire.

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The MSS L_{MIN_λ} - L_{MAX_λ} issue:

- Each satellite has its own unique spectral radiance range associated with its MSS sensor.
- Even though all of the Q_{CAL} DN ranges begin and end with values of 0 and 127 respectively, they do not map the same radiance space (units: W/m^2 sr µm).
- The cross-calibrations of the MSS instruments to L5 MSS cause a shift in the Qcal dynamic ranges of each satellite.

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The $LMIN_\lambda$ - $LMAX_\lambda$ issue defined:

- If a larger dynamic range is used, radiometric resolution is reduced and high saturation values become more difficult to find in later processing stages.
- If a smaller dynamic range is used, then the sensors with larger dynamic ranges would experience low-end and/or high-end clipping, leading to visual striping/banding.

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Calculating Radiance from Q_{CAL}

- Conversion from pixel values (Qcal) to radiance will remain unchanged:

$$L_\lambda = \left(\frac{LMAX_\lambda - LMIN_\lambda}{Q_{CALMAX}} \right) Q_{CAL} + LMIN_\lambda$$

where,

$LMIN_\lambda$ = Spectral radiance at $Q_{CAL} = 0$, and

$LMAX_\lambda$ = Spectral radiance at $Q_{CAL} = Q_{CALMAX}$

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The original $LMIN_\lambda$ - $LMAX_\lambda$ values:

Lmin - Lmax table for MSS:

Processing Dates:	Band 1		Band 2		Band 3		Band 4	
	Lmin	Lmax	Lmin	Lmax	Lmin	Lmax	Lmin	Lmax
Landsat 1	0.0	248.0	0.0	200.0	0.0	176.0	0.0	153.0
L2 (Before 7/16/75)	10.0	210.0	7.0	156.0	7.0	140.0	5.0	138.0
L2 (After 7/16/75)	8.0	263.0	6.0	176.0	6.0	152.0	4.0	130.0
L3 (Pre-launch)	4.0	250.0	3.0	200.0	3.0	165.0	1.0	150.0
L3 (Before 6/1/78)	4.0	220.0	3.0	175.0	3.0	145.0	1.0	147.0
L3 (After 6/1/78)	4.0	259.0	3.0	179.0	3.0	149.0	1.0	128.0
L4 (Before 8/26/82)	2.0	250.0	4.0	180.0	4.0	150.0	3.0	133.0
L4 (8/26/82 - 3/31/83)	2.0	230.0	4.0	180.0	4.0	130.0	3.0	133.0
L4 (After 4/1/83)	4.0	238.0	4.0	164.0	5.0	142.0	4.0	116.0
L5 (Before 4/6/84)	4.0	240.0	3.0	170.0	4.0	150.0	2.0	127.0
L5 (4/6/84 - 11/8/84)	3.0	268.0	3.0	179.0	4.0	159.0	3.0	123.0
L5 (After 11/9/84)	3.0	268.0	3.0	179.0	5.0	148.0	3.0	123.0

Note: For Landsat 1 - 3 the bands 1, 2, 3, & 4 are actually numbered 4, 5, 6, & 7 respectively.
Units = (W/m² sr μm)

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The absolute gain adjusted values:

This Table Displays the Calculated Lmin - Lmax:

Processing Dates:	Band 1		Band 2		Band 3		Band 4	
	Lmin	Lmax	Lmin	Lmax	Lmin	Lmax	Lmin	Lmax
Landsat 1	0.0	243.8	10.0	187.4	-8.9	170.5	0.0	166.5
L2 (Before 7/16/75)	11.0	230.8	0.4	162.9	-1.5	138.8	5.1	139.8
L2 (After 7/16/75)	8.8	288.8	-0.7	184.6	-2.6	151.5	4.1	131.7
L3 (Before 6/1/78)	4.3	239.1	3.0	175.6	3.1	150.1	1.0	146.3
L3 (After 6/1/78)	4.4	284.7	3.0	179.6	3.1	154.3	1.0	127.4
L4 (Before 8/26/82)	2.3	283.5	4.3	194.5	4.2	157.8	3.1	137.6
L4 (8/26/82 - 3/31/83)	2.3	260.8	4.3	194.5	4.2	136.7	3.1	137.6
L4 (After 4/1/83)	4.5	269.8	4.3	177.2	5.3	149.3	4.1	120.0
L5 (Before 4/6/84)	4.0	240.0	3.0	170.0	4.0	150.0	2.0	127.0
L5 (4/6/84 - 11/8/84)	3.0	268.0	3.0	179.0	4.0	159.0	3.0	123.0
L5 (After 11/9/84)	3.0	268.0	3.0	179.0	5.0	148.0	3.0	123.0

Note: For Landsat 1 - 3 the bands 1, 2, 3, & 4 are actually numbered 4, 5, 6, & 7 respectively.
Units = (W/m² sr µm)

Note:
The values shown in red font are dependent upon a TDF, and will continuously change over the lifetime of the instrument.

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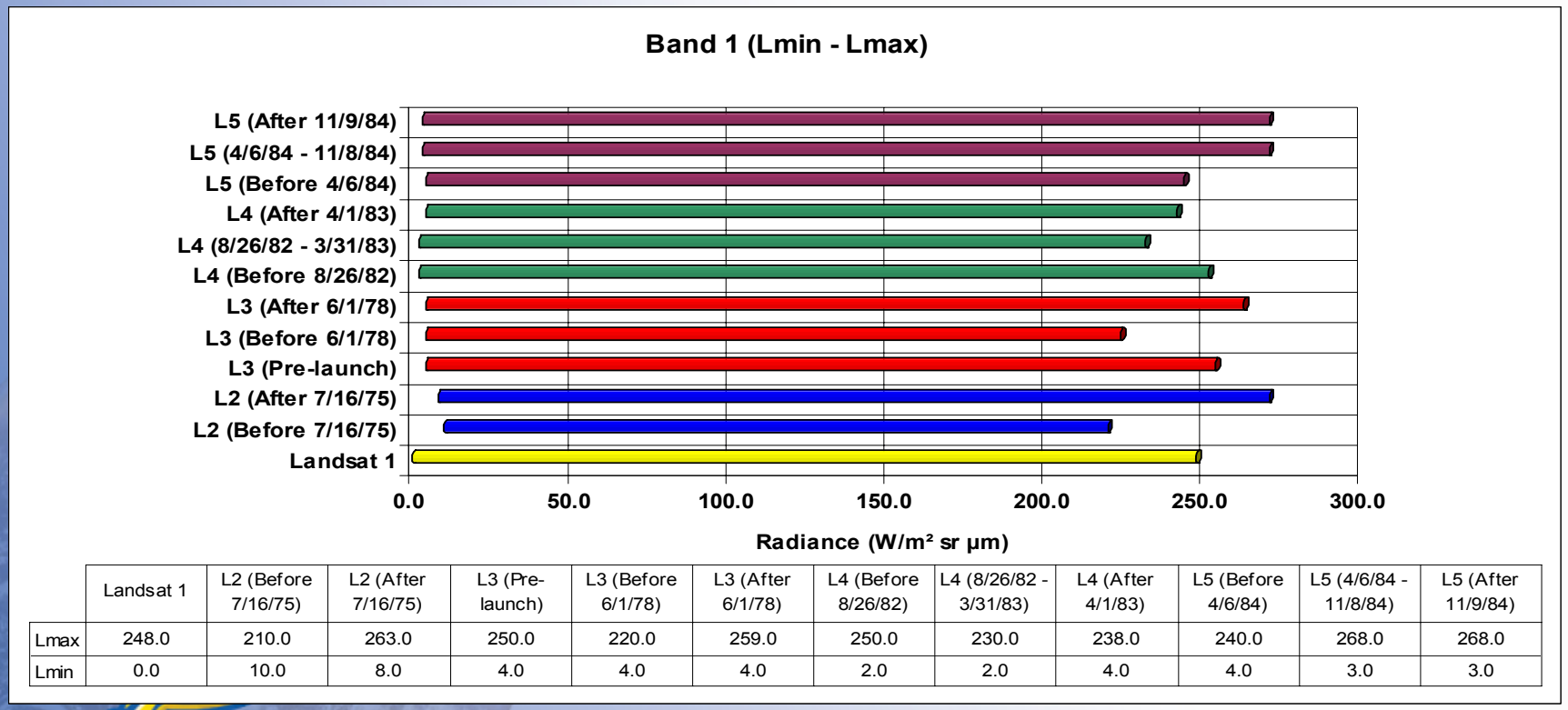
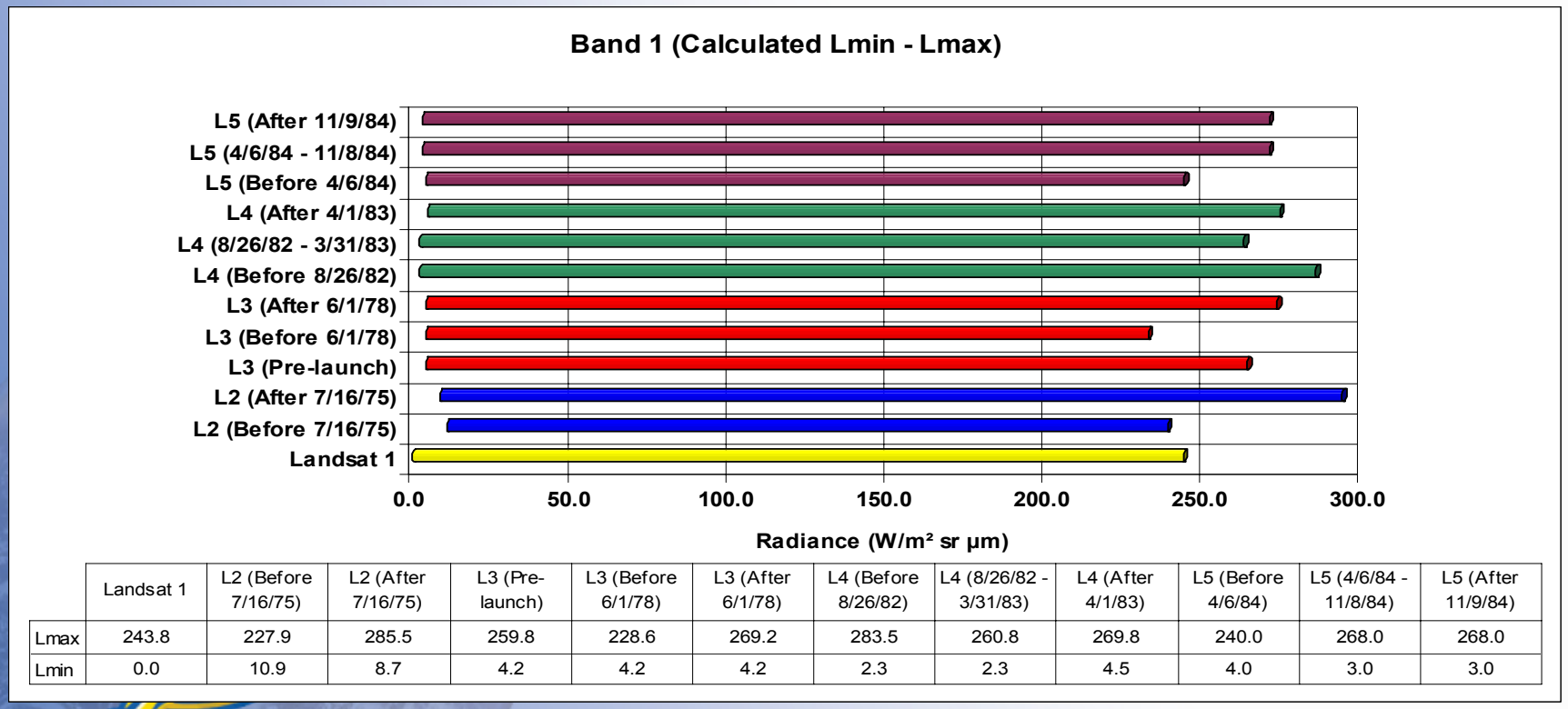
Lmin – Lmax (Band 1):



	Landsat 1	L2 (Before 7/16/75)	L2 (After 7/16/75)	L3 (Pre-launch)	L3 (Before 6/1/78)	L3 (After 6/1/78)	L4 (Before 8/26/82)	L4 (8/26/82 - 3/31/83)	L4 (After 4/1/83)	L5 (Before 4/6/84)	L5 (4/6/84 - 11/8/84)	L5 (After 11/9/84)
Lmax	248.0	210.0	263.0	250.0	220.0	259.0	250.0	230.0	238.0	240.0	268.0	268.0
Lmin	0.0	10.0	8.0	4.0	4.0	4.0	2.0	2.0	4.0	4.0	3.0	3.0

Lmin – Lmax (Band 1): Adjusted



	Landsat 1	L2 (Before 7/16/75)	L2 (After 7/16/75)	L3 (Pre-launch)	L3 (Before 6/1/78)	L3 (After 6/1/78)	L4 (Before 8/26/82)	L4 (8/26/82 - 3/31/83)	L4 (After 4/1/83)	L5 (Before 4/6/84)	L5 (4/6/84 - 11/8/84)	L5 (After 11/9/84)
Lmax	243.8	227.9	285.5	259.8	228.6	269.2	283.5	260.8	269.8	240.0	268.0	268.0
Lmin	0.0	10.9	8.7	4.2	4.2	4.2	2.3	2.3	4.5	4.0	3.0	3.0

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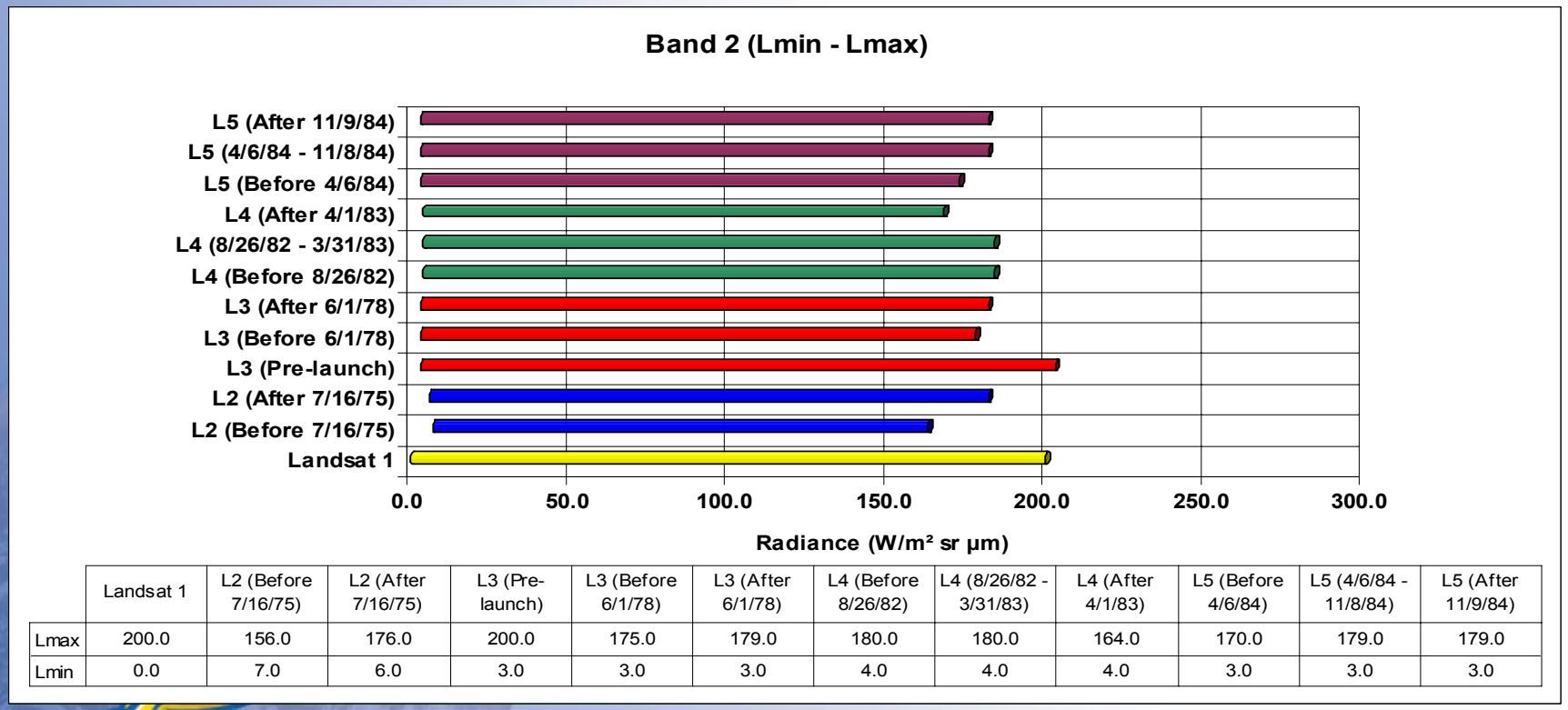
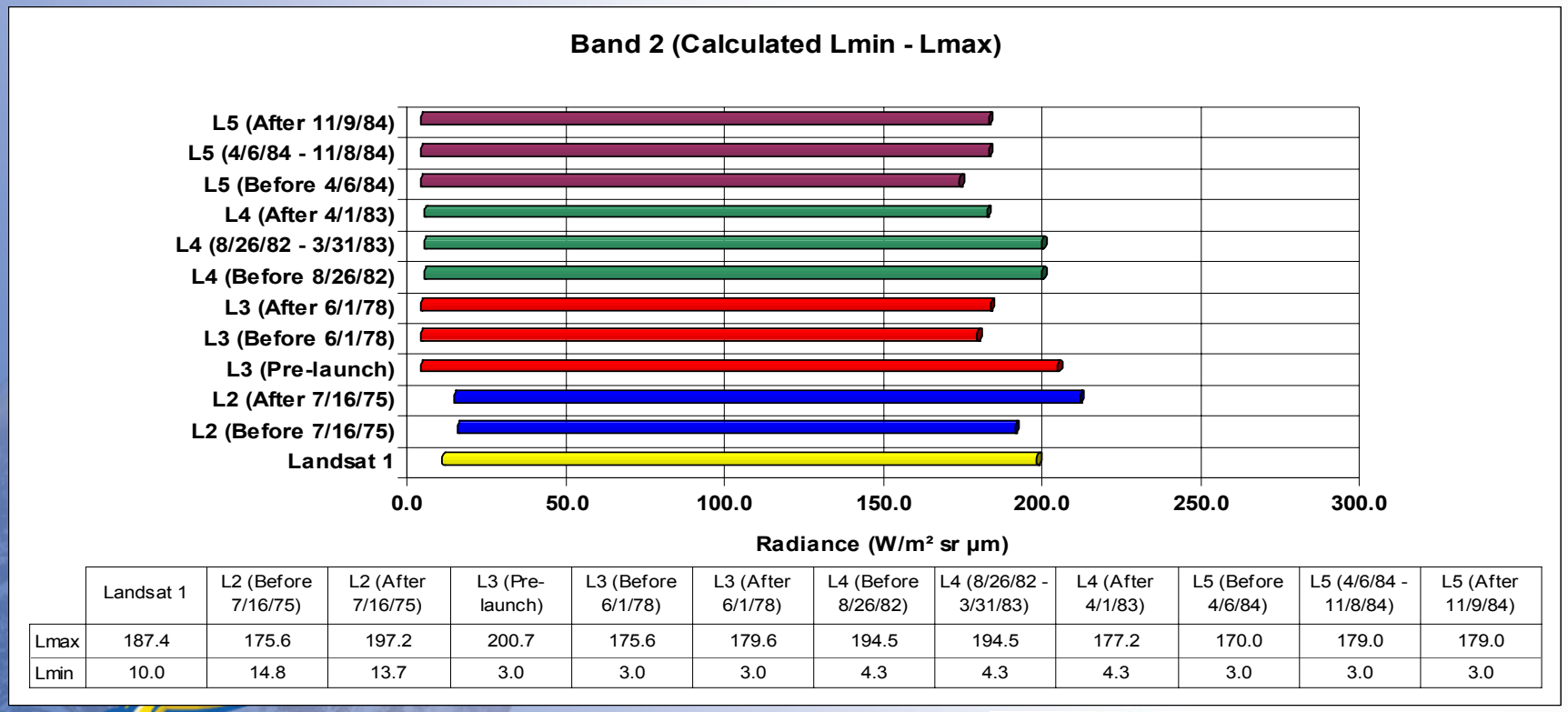
Lmin – Lmax (Band 2):



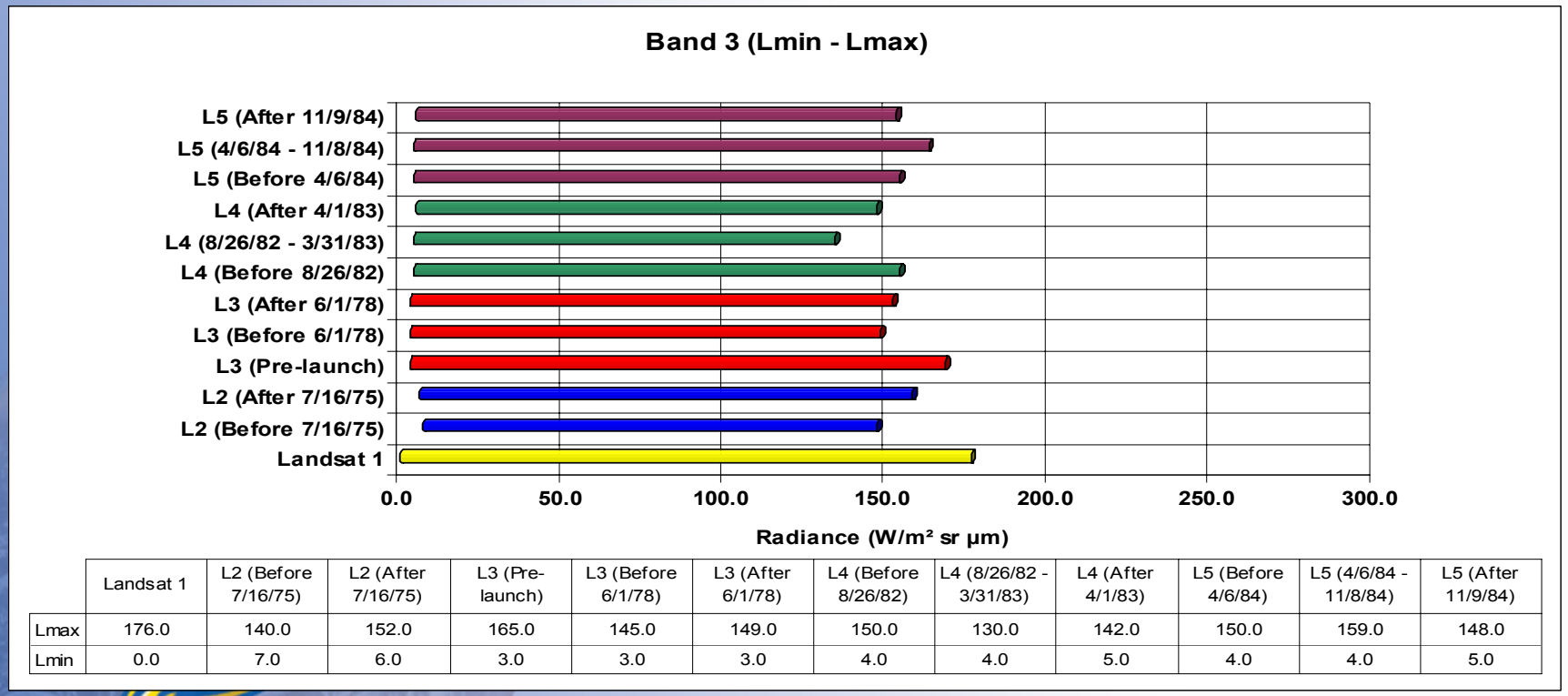
	Landsat 1	L2 (Before 7/16/75)	L2 (After 7/16/75)	L3 (Pre-launch)	L3 (Before 6/1/78)	L3 (After 6/1/78)	L4 (Before 8/26/82)	L4 (8/26/82 - 3/31/83)	L4 (After 4/1/83)	L5 (Before 4/6/84)	L5 (4/6/84 - 11/8/84)	L5 (After 11/9/84)
Lmax	200.0	156.0	176.0	200.0	175.0	179.0	180.0	180.0	164.0	170.0	179.0	179.0
Lmin	0.0	7.0	6.0	3.0	3.0	3.0	4.0	4.0	4.0	3.0	3.0	3.0

Lmin – Lmax (Band 2): Adjusted



	Landsat 1	L2 (Before 7/16/75)	L2 (After 7/16/75)	L3 (Pre-launch)	L3 (Before 6/1/78)	L3 (After 6/1/78)	L4 (Before 8/26/82)	L4 (8/26/82 - 3/31/83)	L4 (After 4/1/83)	L5 (Before 4/6/84)	L5 (4/6/84 - 11/8/84)	L5 (After 11/9/84)
Lmax	187.4	175.6	197.2	200.7	175.6	179.6	194.5	194.5	177.2	170.0	179.0	179.0
Lmin	10.0	14.8	13.7	3.0	3.0	3.0	4.3	4.3	4.3	3.0	3.0	3.0

Lmin – Lmax (Band 3):



	Landsat 1	L2 (Before 7/16/75)	L2 (After 7/16/75)	L3 (Pre-launch)	L3 (Before 6/1/78)	L3 (After 6/1/78)	L4 (Before 8/26/82)	L4 (8/26/82 - 3/31/83)	L4 (After 4/1/83)	L5 (Before 4/6/84)	L5 (4/6/84 - 11/8/84)	L5 (After 11/9/84)
Lmax	176.0	140.0	152.0	165.0	145.0	149.0	150.0	130.0	142.0	150.0	159.0	148.0
Lmin	0.0	7.0	6.0	3.0	3.0	3.0	4.0	4.0	5.0	4.0	4.0	5.0

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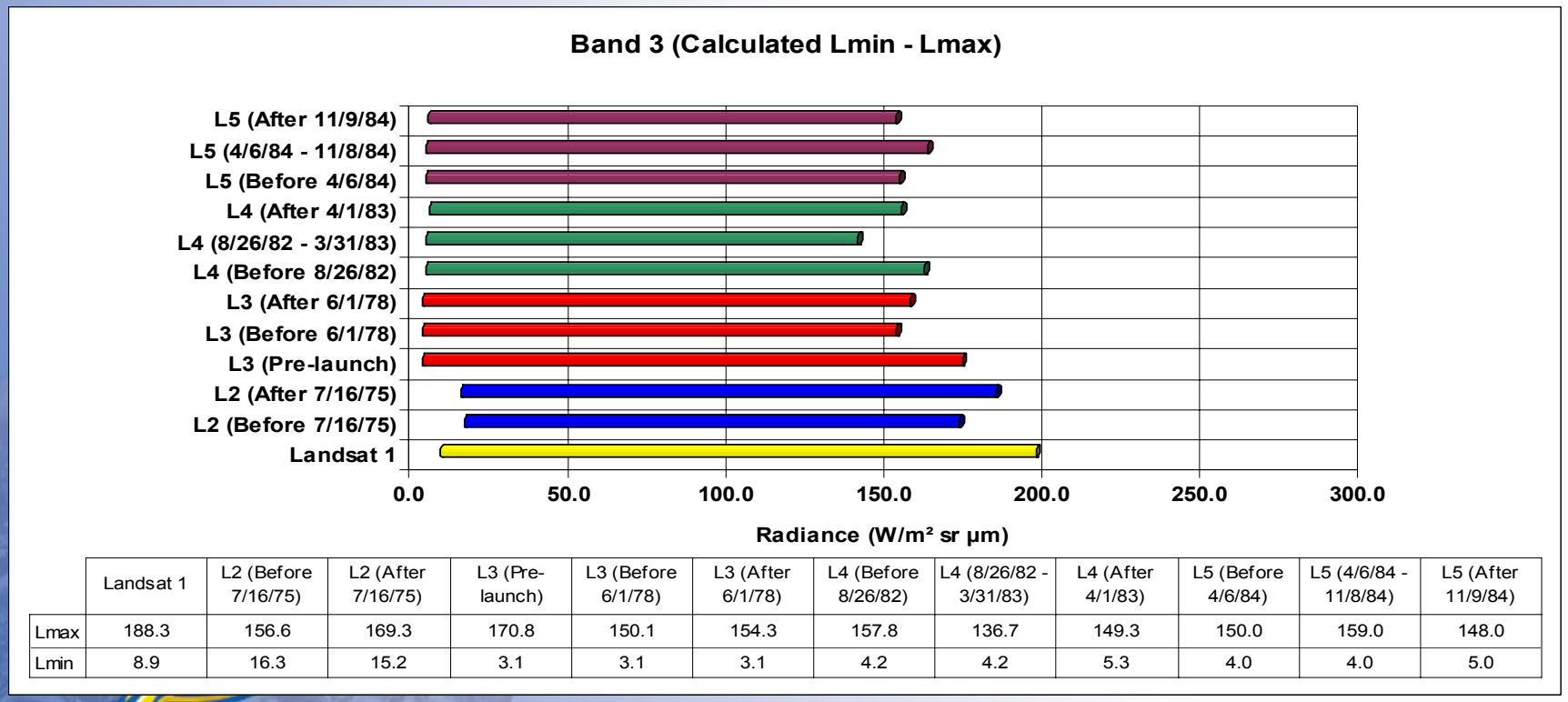
Lmin – Lmax (Band 3): Adjusted



	Landsat 1	L2 (Before 7/16/75)	L2 (After 7/16/75)	L3 (Pre-launch)	L3 (Before 6/1/78)	L3 (After 6/1/78)	L4 (Before 8/26/82)	L4 (8/26/82 - 3/31/83)	L4 (After 4/1/83)	L5 (Before 4/6/84)	L5 (4/6/84 - 11/8/84)	L5 (After 11/9/84)
Lmax	188.3	156.6	169.3	170.8	150.1	154.3	157.8	136.7	149.3	150.0	159.0	148.0
Lmin	8.9	16.3	15.2	3.1	3.1	3.1	4.2	4.2	5.3	4.0	4.0	5.0

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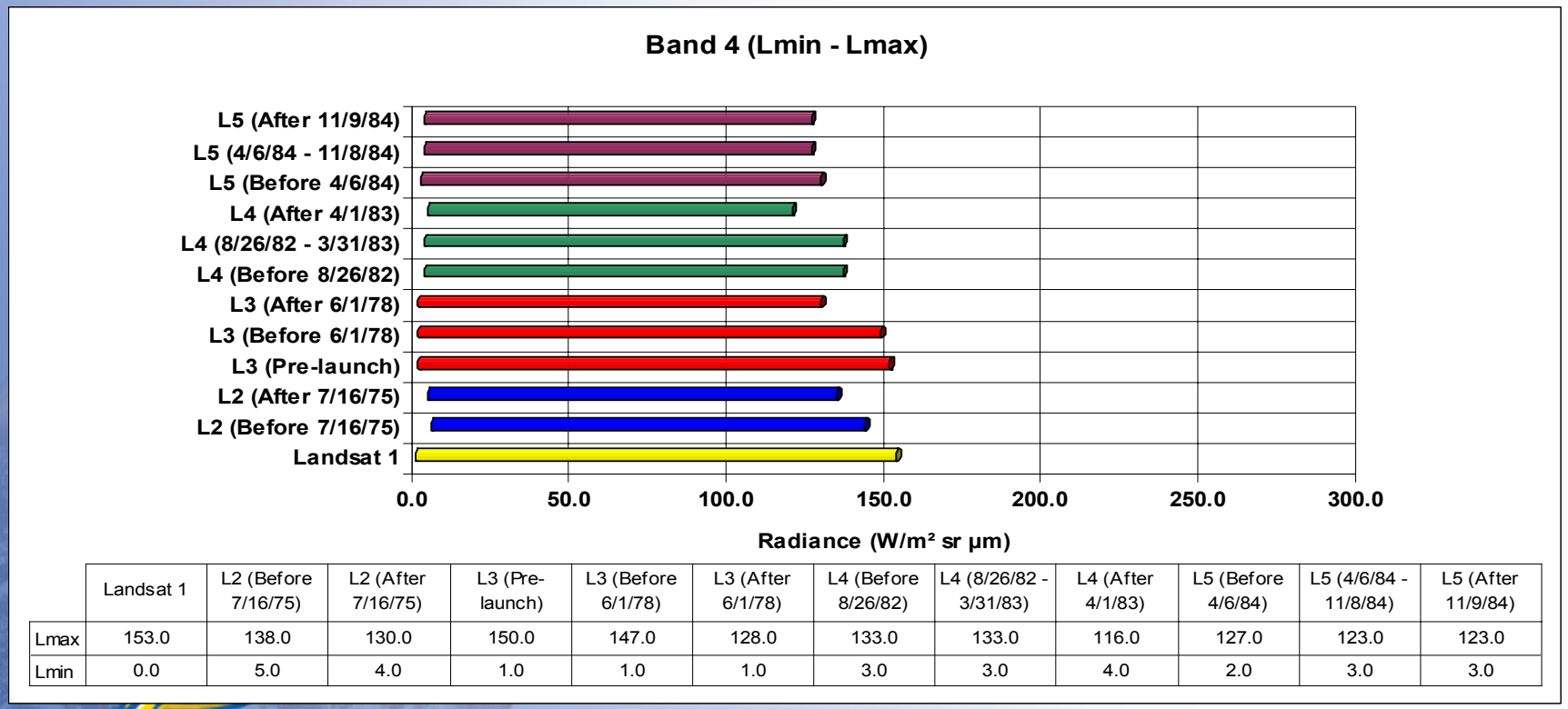
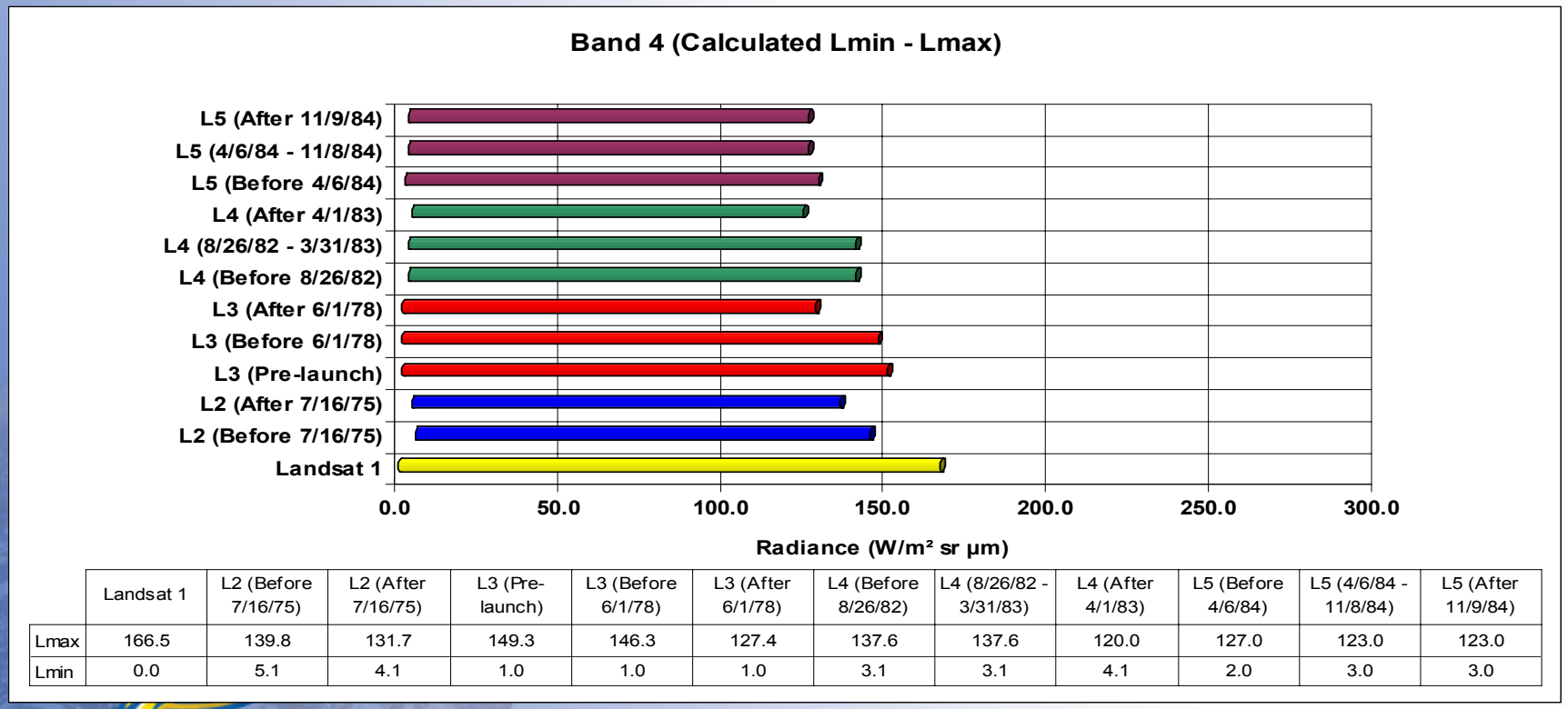
Lmin – Lmax (Band 4):



	Landsat 1	L2 (Before 7/16/75)	L2 (After 7/16/75)	L3 (Pre-launch)	L3 (Before 6/1/78)	L3 (After 6/1/78)	L4 (Before 8/26/82)	L4 (8/26/82 - 3/31/83)	L4 (After 4/1/83)	L5 (Before 4/6/84)	L5 (4/6/84 - 11/8/84)	L5 (After 11/9/84)
Lmax	153.0	138.0	130.0	150.0	147.0	128.0	133.0	133.0	116.0	127.0	123.0	123.0
Lmin	0.0	5.0	4.0	1.0	1.0	1.0	3.0	3.0	4.0	2.0	3.0	3.0

Lmin – Lmax (Band 4): Adjusted



	Landsat 1	L2 (Before 7/16/75)	L2 (After 7/16/75)	L3 (Pre-launch)	L3 (Before 6/1/78)	L3 (After 6/1/78)	L4 (Before 8/26/82)	L4 (8/26/82 - 3/31/83)	L4 (After 4/1/83)	L5 (Before 4/6/84)	L5 (4/6/84 - 11/8/84)	L5 (After 11/9/84)
Lmax	166.5	139.8	131.7	149.3	146.3	127.4	137.6	137.6	120.0	127.0	123.0	123.0
Lmin	0.0	5.1	4.1	1.0	1.0	1.0	3.1	3.1	4.1	2.0	3.0	3.0

The TDF Adjusted Bands

This Table Displays the Calculated Lmin - Lmax:

Processing Dates:	Band 1		Band 2		Band 3		Band 4	
	Lmin	Lmax	Lmin	Lmax	Lmin	Lmax	Lmin	Lmax
Landsat 1	0.0	243.8	10.0	187.4	-8.9	170.5	0.0	166.5
L2 (Before 7/16/75)	11.0	230.8	0.4	162.9	-1.5	138.8	5.1	139.8
L2 (After 7/16/75)	8.8	288.8	-0.7	184.6	-2.6	151.5	4.1	131.7
L3 (Before 6/1/78)	4.3	239.1	3.0	175.6	3.1	150.1	1.0	146.3
L3 (After 6/1/78)	4.4	284.7	3.0	179.6	3.1	154.3	1.0	127.4
L4 (Before 8/26/82)	2.3	283.5	4.3	194.5	4.2	157.8	3.1	137.6
L4 (8/26/82 - 3/31/83)	2.3	260.8	4.3	194.5	4.2	136.7	3.1	137.6
L4 (After 4/1/83)	4.5	269.8	4.3	177.2	5.3	149.3	4.1	120.0
L5 (Before 4/6/84)	4.0	240.0	3.0	170.0	4.0	150.0	2.0	127.0
L5 (4/6/84 - 11/8/84)	3.0	268.0	3.0	179.0	4.0	159.0	3.0	123.0
L5 (After 11/9/84)	3.0	268.0	3.0	179.0	5.0	148.0	3.0	123.0

Note: For Landsat 1 - 3 the bands 1, 2, 3, & 4 are actually numbered 4, 5, 6, & 7 respectively.

Units = (W/m^2 sr µm)

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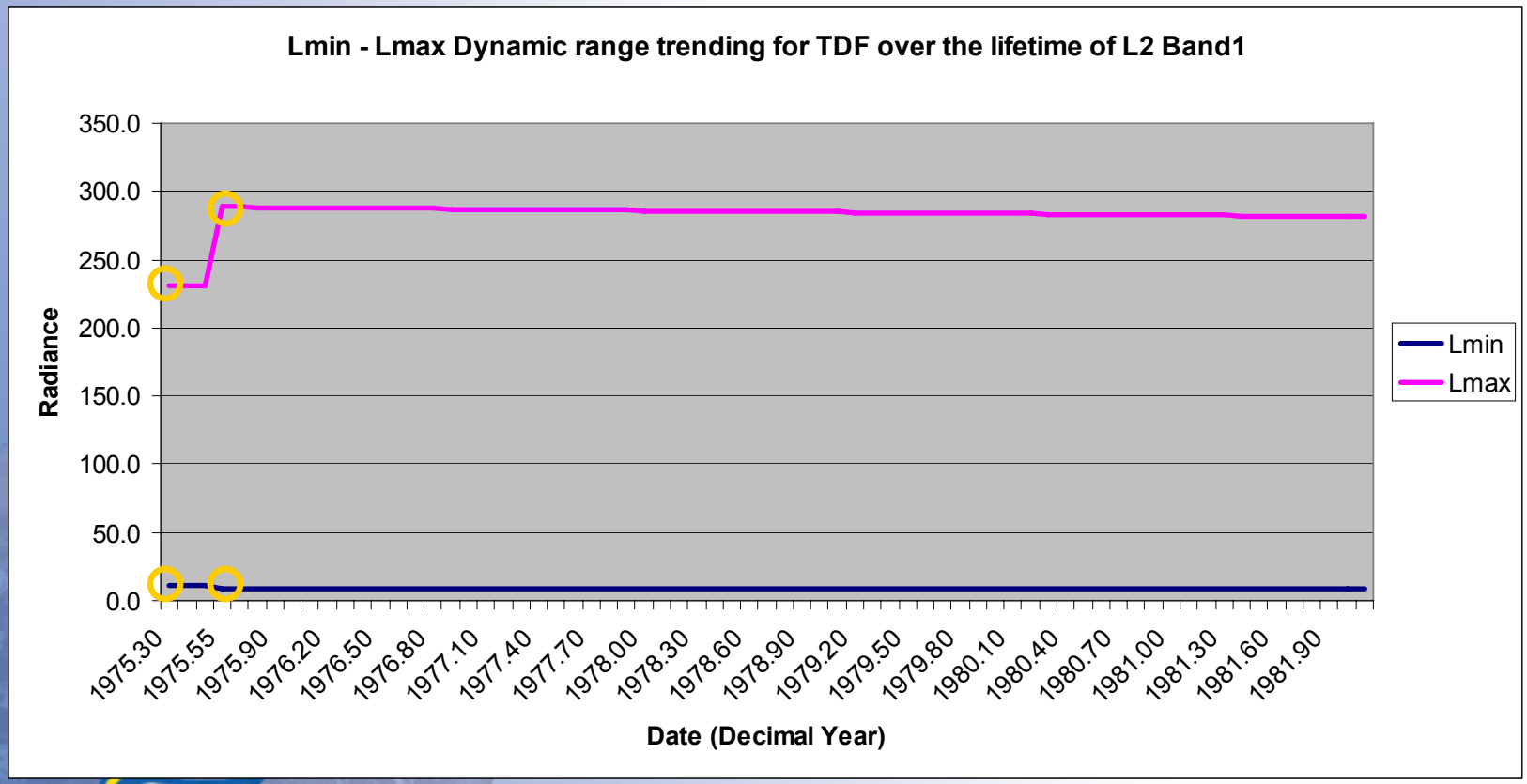
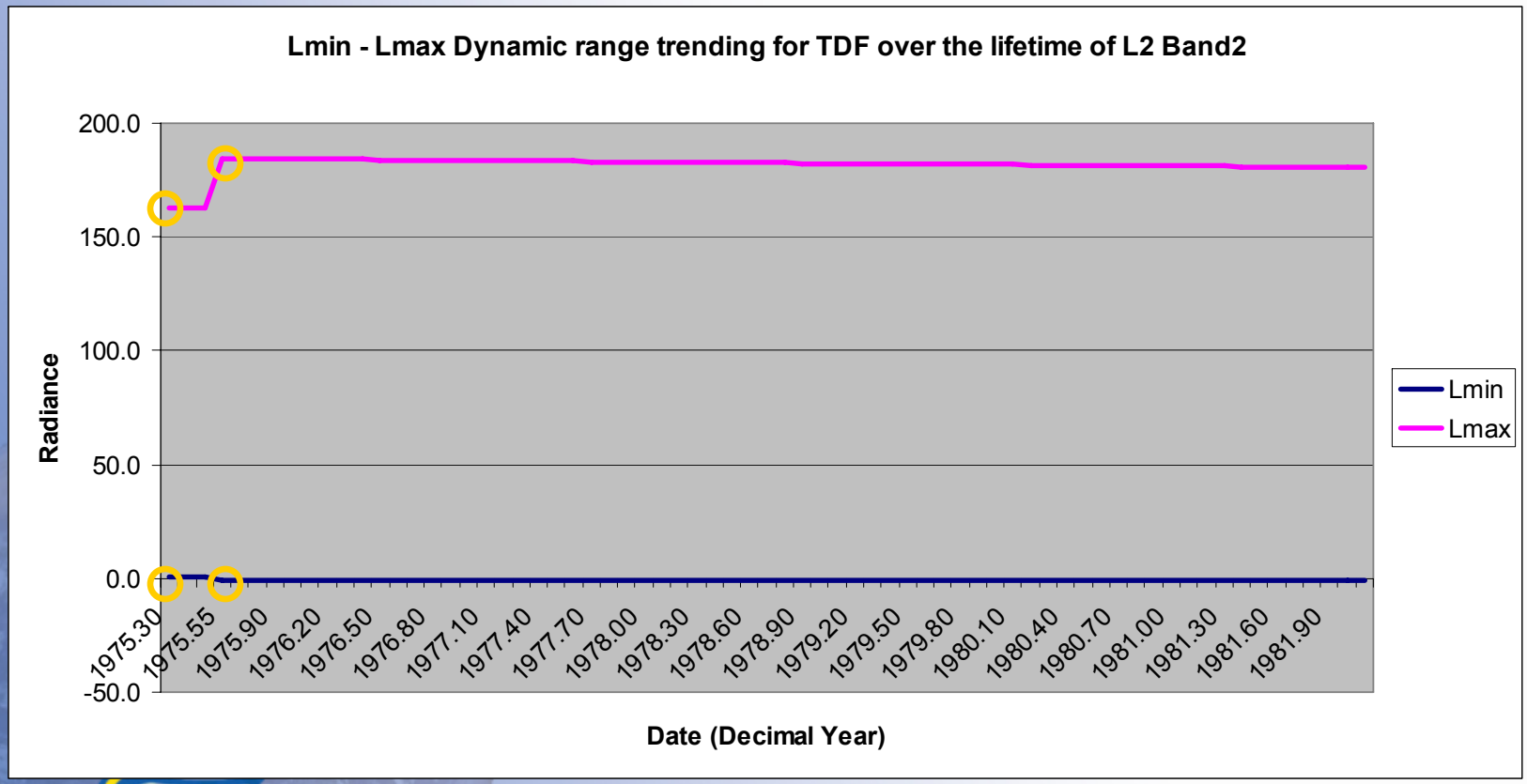
L2, Band 1 TDF Lifetime Trend



L2, Band 1 MSS undergoes a 2.3% change for Lmin (0.2 radiance), and a 2.6% change for Lmax (7.2 radiance). Note: This does not include the transitional period at the beginning of each sensor's lifetime.

L2, Band 2 TDF Lifetime Trend



L2, Band 2 MSS undergoes a 16.5% change for Lmin (0.13 radiance), and a 2.2% change for Lmax (3.92 radiance).
Note: This does not include the transitional period at the beginning of each sensor's lifetime.

The TDF Adjusted Bands

Landsat 2 TDF Ranges

Processing Dates:	Band 1 Lmin	Band 1 Lmax	Band 2 Lmin	Band 2 Lmax	TDF Date
L2 (Before 7/16/75)	11.0	230.8	0.42	162.89	1975.29
L2 (Before 7/16/75)	11.0	230.6	0.41	162.76	1975.54
L2 (After 7/16/75)	8.8	288.8	-0.68	184.55	1975.54
L2 (After 7/16/75)	8.6	281.6	-0.81	180.63	1982.04

Note: For Landsat 1 - 3 the bands 1, 2, 3, & 4 are actually numbered 4, 5, 6, & 7 respectively.
Units = (W/m² sr µm)

Landsat 3 TDF Ranges

Processing Dates:	Band 1 Lmin	Band 1 Lmax	TDF Date
L3 (Before 6/1/78)	4.3	239.1	1978.18
L3 (Before 6/1/78)	4.3	238.9	1978.42
L3 (After 6/1/78)	4.4	284.7	1978.42
L3 (After 6/1/78)	4.3	269.2	1983.91

Note: For Landsat 1 - 3 the bands 1, 2, 3, & 4 are actually numbered 4, 5, 6, & 7 respectively.
Units = (W/m² sr µm)

The TDF difference Changes:

L2	% change Lmin	% change Lmax
B1	2.3	2.6
B2	16.5	2.2

L3	% change Lmin	% change Lmax
B1	2.8	5.5

Notice the change in the Lmin and Lmax values over the lifetime of the sensor.

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Switching to an 8-bit Product

- By switching MSS over to an 8-bit image, we expand the digital number range from a maximum of 127 to 255.
- This range would be large enough to cover the entire spectral radiance dynamic range across all five sensors without losing spectral resolution when mapped back to Q_{CAL} space.
- The disadvantage of converting the images over to 8-bit is deciding how to deal with high-level pixel saturation.

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Solutions (1)

- All products are 8 bit.
- Consensus was reached to 'stretch' the images across the entire dynamic range.
  - $L_{MIN} \rightarrow Qcal_{MIN} + 1 \rightarrow 1$
  - $L_{MAX} \rightarrow Qcal_{MAX} \rightarrow 255$
- High/Low Saturation accounted for:
  - This placed original 0 DN pixels at 1 DN.
  - This places the original 127 DN saturated pixels to a maximum value of 255 DN.
- To resolve the TDF issue it has been decided to place the Lmin and Lmax values to their maximum difference.

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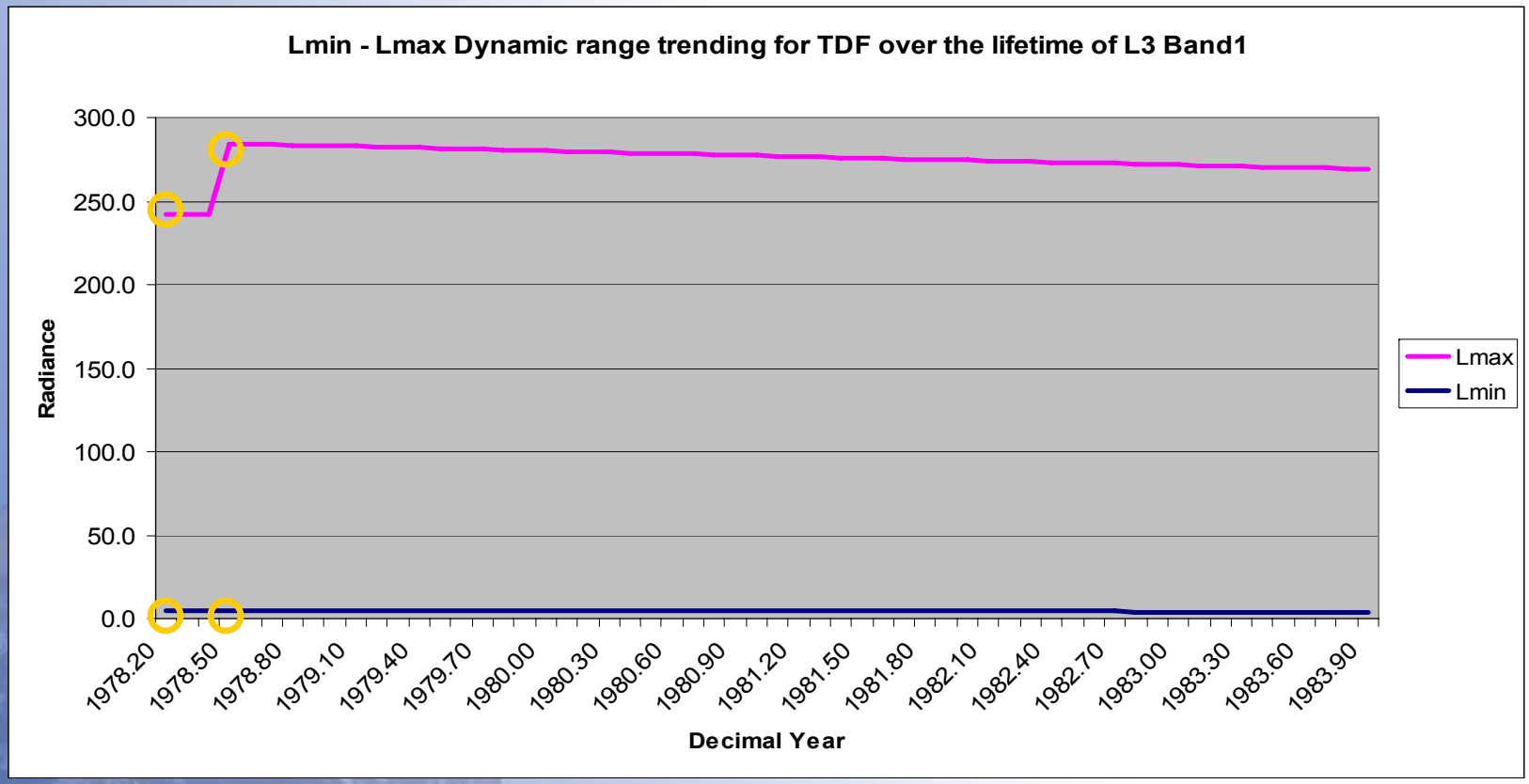
L3, Band 1 TDF Lifetime Trend



L3, Band 1 MSS undergoes a 2.8% change for Lmin (0.1 radiance), and a 5.5% change for Lmax (15.5 radiance). Note: This does not include the transitional period at the beginning of each sensor's lifetime.

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Solutions (2)

- The ***Lmin – Lmax adjusted*** Qcal values will be used as the final dynamic range for each MSS sensor.
- Two sets of Lmin – Lmax cpf parameters will be used to cover the historic processing changes made within the lifetime of each sensor.
- The bands that are affected by the TDFs will be set to the maximum Lmax value to refrain from truncating additional pixels into saturation (Lmin change across lifetime is minimal).
  - Originally saturated pixels (i.e. '127s') will be tracked and set to '255'.

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Final CPF Values

This Table Displays the Final Calculated Lmin - Lmax:

Processing Dates:	Band 1		Band 2		Band 3		Band 4	
	Lmin	Lmax	Lmin	Lmax	Lmin	Lmax	Lmin	Lmax
Landsat 1	0.0	243.8	10.0	187.4	-8.9	170.5	0.0	166.5
L2 (Before 7/16/75)	11.0	230.8	0.4	162.9	-1.5	138.8	5.1	139.8
L2 (After 7/16/75)	8.8	288.8	-0.7	184.6	-2.6	151.5	4.1	131.7
L3 (Before 6/1/78)	4.3	239.1	3.0	175.6	3.1	150.1	1.0	146.3
L3 (After 6/1/78)	4.4	284.7	3.0	179.6	3.1	154.3	1.0	127.4
L4 (Before 8/26/82)	2.3	283.5	4.3	194.5	4.2	157.8	3.1	137.6
L4 (8/26/82 - 3/31/83)	2.3	260.8	4.3	194.5	4.2	136.7	3.1	137.6
L4 (After 4/1/83)	4.5	269.8	4.3	177.2	5.3	149.3	4.1	120.0
L5 (Before 4/6/84)	4.0	240.0	3.0	170.0	4.0	150.0	2.0	127.0
L5 (4/6/84 - 11/8/84)	3.0	268.0	3.0	179.0	4.0	159.0	3.0	123.0
L5 (After 11/9/84)	3.0	268.0	3.0	179.0	5.0	148.0	3.0	123.0

Note: For Landsat 1 - 3 the bands 1, 2, 3, & 4 are actually numbered 4, 5, 6, & 7 respectively.

Units = (W/m² sr µm)

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Caveat Emptor:
Let the ‘free data user’ be
<spectrally> aware!

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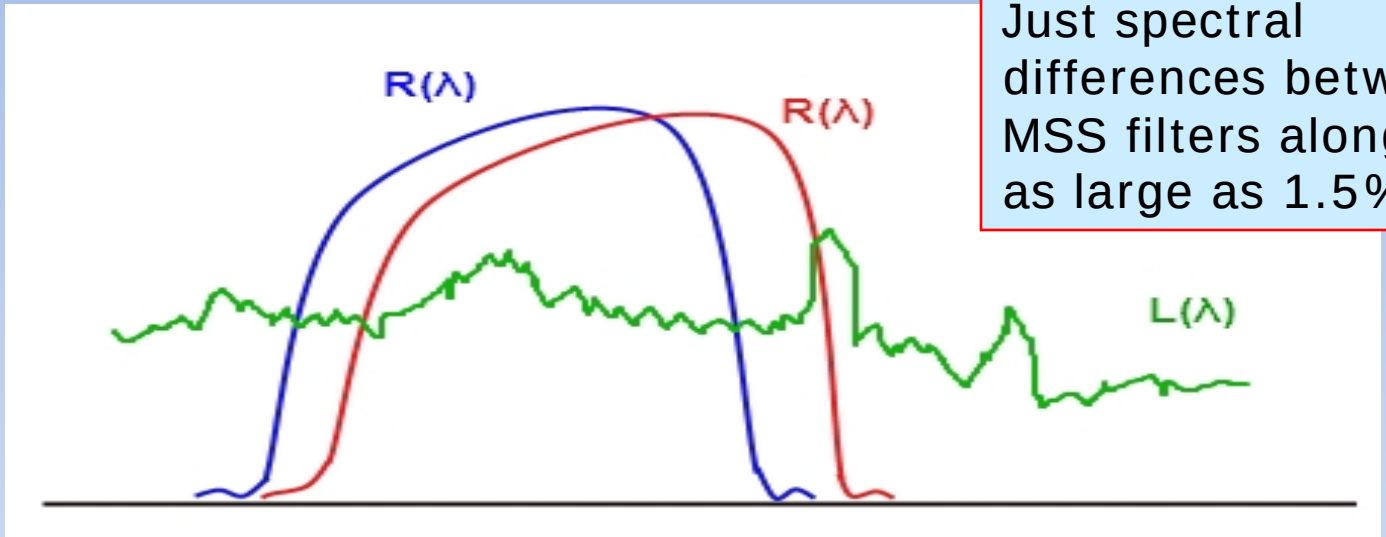
R(λ): Band specific RSR Profile

L(λ): Spectral signature of target

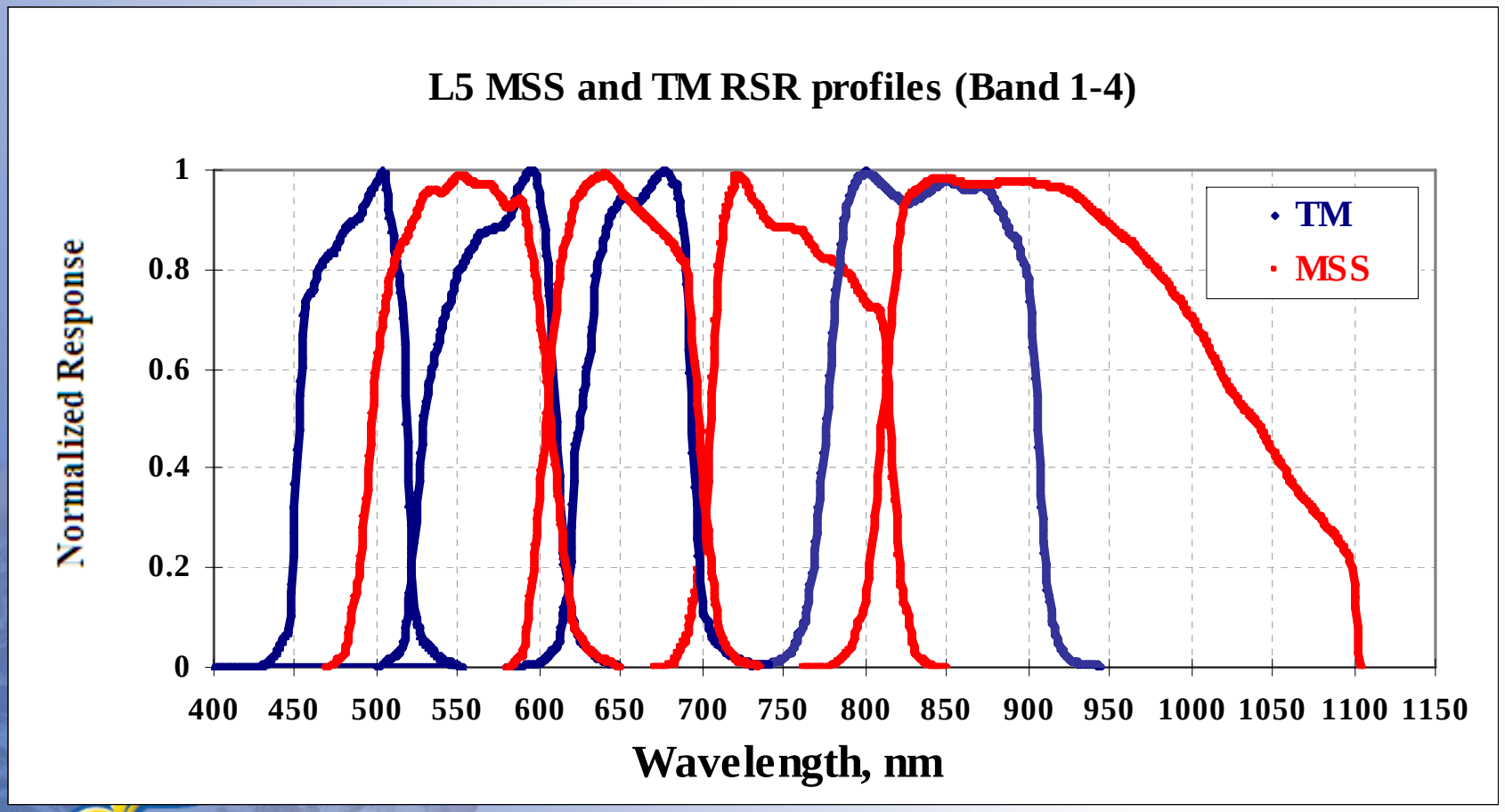


Just spectral differences between MSS filters along is as large as 1.5%!

$$SBAF = \frac{(\int R(\lambda).L(\lambda)\, d\lambda / \int R(\lambda).d\lambda)}{(\int R(\lambda).L(\lambda) d\lambda / \int R(\lambda)\, .d\lambda)}$$

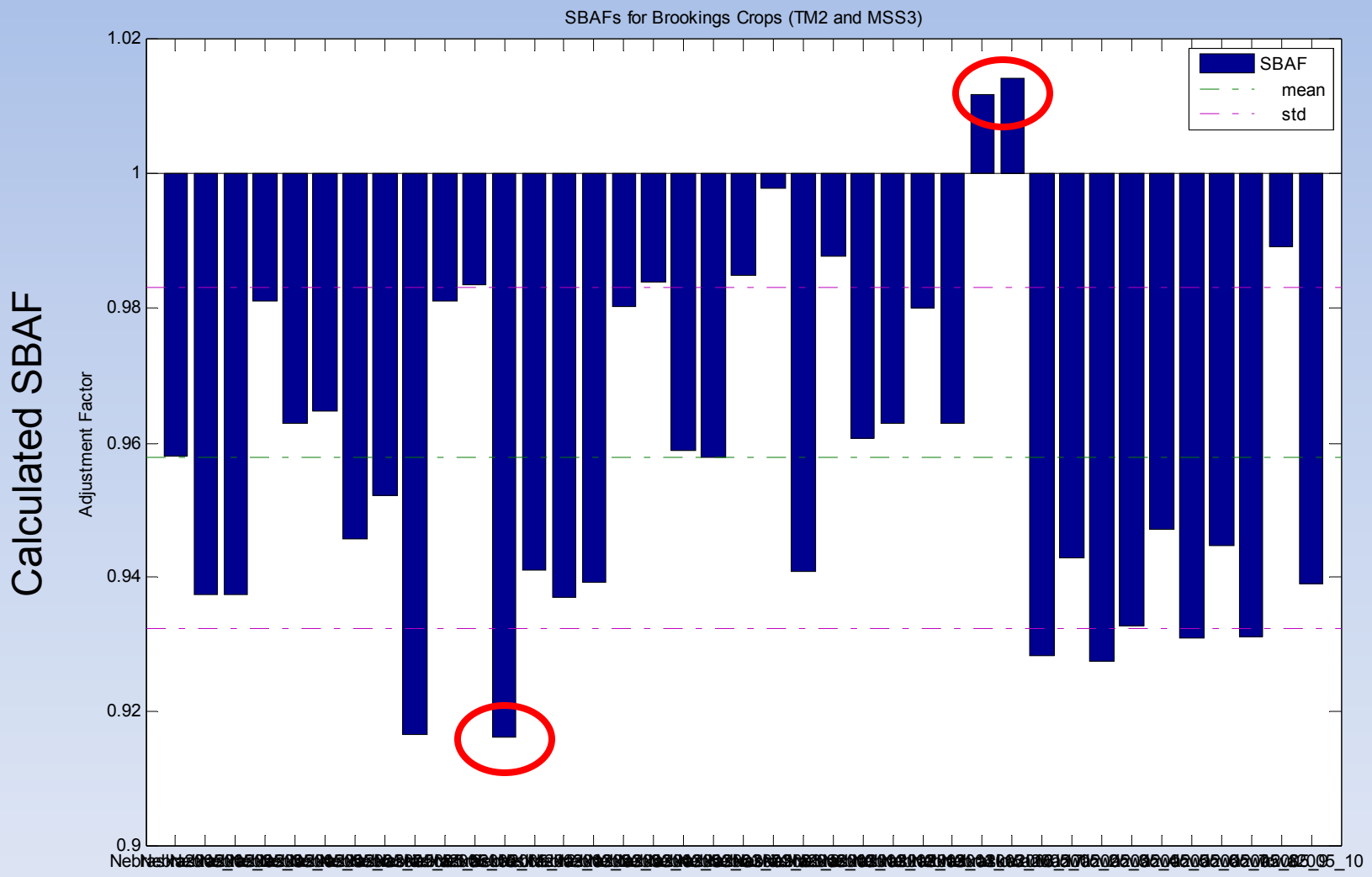
- This phenomena is accounted for using a Spectral Band Adjustment Factor (SBAF).
- The SBAF uses a known Spectral Signature of a ground target to adjust for these differences of two different sensor bands by calculating the reflectance seen by each sensor of a specific ground target's spectral signature. Therefore, SBAFs are specific to each ground target.

TM & MSS are different beasts spectrally



TM to MSS Vegetation Comparisons

TM2/MSS1 SBAFs calculated from Brookings crops—vary from 0.91 to 1.01



Each bar represents a different ROI Crop in a Hyperion Scene

Summary

- The absolute gains of five MSS sensors exhibit a maximum difference of 17% which has been reduced to less than 1% in Band 1, 2% in Band 2, 3% in Band 3, and 5% in Band 4
- Lmin/Lmax approach and values have been defined for each sensor for ease of use on an 8 bit scale. Conversion to radiance procedure is unchanged.
- Spectral differences within MSS sensors can contribute errors approaching 2%. Spectral differences between MSS and TM sensors can lead to 10% errors with vegetated targets.
- MSS Absolute Calibration estimate forthcoming.